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A MICROSCOPIC STUDY OF CONIFEROUS WOOD IN RELATION TO ITS STRENGTH PROPERTIES[1]

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I. Introduction

In a broad sense this study is motivated by a desire to add to the meager knowledge of the role played by the individual cells in the resistance of the wood to mechanical forces. More specifically, the problem is concerned with the identification of wood which is abnormally low in strength. Since it is recognized that woods of greater density are the stronger, an abnormal-strength specimen is one that is weaker than the average for the density range in which it occurs.

Research on the strength properties of wood has been quite empirical, and the data given have represented large numbers of specimens either as average values or as average trends of relationships. Winslow ('33), in outlining the state of research in forest products, has this to say of the mechanical properties of wood:

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The information we possess as to strength properties has been collected with only incidental reference to structure; the direction (longitudinal, radial, or tangential) in which the force was applied was commonly known, and one structural characteristic, density, was always determined. The finer details of structure were not determined, however, nor were the tests designed to show the effect of structural variations in any minute degree.

Thus there is no considerable body of literature bearing directly upon the cellular variations related to strength. One type of clear coniferous wood of abnormal-strength properties has been known for over forty years, but until recently its description has been vague. Whether this is the only type of abnormality is not known, nor is it known whether the factors causing this abnormality are also responsible for what might be called the normal variation of strength in relation to density.

The purpose of this study is not the investigation of any given type of structural variation, but the investigation with the microscope of the differences between strong and weak specimens of a wood of simple anatomy that have been subjected to simple stresses. Further, an interpretation of the microscopic data is attempted against a background of the literature pertaining to factors known to affect the strength of wood.

II. Review of the Factors Affecting the Strength of Wood

Although the experimental part of this problem is only intended to constitute a step in the direction of complete control of the factors affecting strength of wood, a review of what is known of these factors is necessary for a full understanding of the problem, the methods used, and for an interpretation of the results. The discussion will be concerned with coniferous wood except where work on other wood applies, and the characteristics of southern pine will be emphasized.

Because it is at present the only generally known type of clear coniferous wood of abnormal-strength properties, "compression wood" will be frequently referred to in this paper. The term is synonymous with the German expressions "Rotholz" and "Druckholz." Büsgen and Münch ('29) gave a

good account of its causes and occurrence, and Trendelenburg ('32) and Pillow and Luxford ('37) have recently reviewed its technical properties. The literature will not be reviewed here, but it is of interest to note that Roth ('95) recognized the structure in the trunks of southern pine, but seems to have been ignorant of the properties of the wood. There has been some confusion in the descriptions of "compression wood," so that it would be well to quote from the summary of the most recent and the most comprehensive paper on the subject, that by Pillow and Luxford ('37):

> Under a microscope the summerwood tracheids of compression wood appear to be nearly circular in cross section whereas those of normal wood are more or less rectangular. The fibrils of the secondary cell walls in compression wood make a higher angle in relation to the longest axis of the cells than do the fibrils in normal wood and these walls contain microscopic checks.
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> The lignin content of compression wood as indicated by the species investigated is slightly higher and the cellulose content slightly lower than normal wood. The weight of pronounced compression wood is from 15 to 40 per cent greater than normal wood. The longitudinal shrinkage of compression wood from the green to oven-dry condition varies from about 0.3 to 2.5 percent whereas normal wood has a shrinkage from about 0.1 to 0.2 percent. The transverse shrinkage of compression wood is less than that of normal wood.
>
> When adjustments are made for differences in weight, compression wood is lower in practically all strength properties as compared to normal wood. . . . The increase in strength properties accompanying drying of the wood is not so great for compression wood as for normal wood. Compression wood is under compression in the log and when the stresses are released, such as by sawing, extension of the compression wood portion occurs.

There is still much to be known about this type of wood, but until a more descriptive term can be applied, it must be referred to by its accepted English designation, "compression wood." It will be used in this paper with quotation marks to avoid associating it with the compression strength properties.

There may also be reference to the German terms "Weissholz" and "Zugholz" (tension wood) which have been applied to the wood diametrically opposite in the stem to "Rotholz."

DENSITY

The two factors controlling density of wood are the density of wood substance (cell-wall material) and the porosity or proportion of air space to cell-wall volume. The apparent

density of wood substance seems to be one of the most invariable features of wood. Hartig ('85) was satisfied to use the single value 1.56 for several species of conifers. Dunlap ('14) found a range of 4.5 per cent in seven species including hardwoods and softwoods, but only insignificant variation between two determinations of the same species. He found 1.506 gr. per cc. for longleaf pine by floating thin sections in a calibrated solution of calcium nitrate. Stamm ('29) made a study of the density of wood substance and came to the conclusion that it "varies slightly among species as a result of variation in the chemical composition of the substance." He obtained densities of 1.598 for cotton cellulose, 1.594 for isolated Cross and Bevan wood cellulose (from catalpa heartwood), 1.451 for isolated lignin (insoluble in 72 per cent H_2SO_4, from western yellow pine heartwood), and 1.531 for loblolly pine wood substance. All these data were from the same method, water displacement at 25° C. Berkley ('34), using a pycnometer method on sawdust, found a range of 1.5156 to 1.5273 gr. per cc. embracing three species of southern pine.[1] It seems evident that variation in cell-wall density has little to contribute to the wide variation observed in the strength of woods of the same specific gravity. Also it appears justifiable to use the specific gravity of wood as a criterion of the relative amount of wood substance in a specimen, at least in a series from the same kind of wood.

The real basis, then, for the strength-specific gravity correlation which is known for wood is the relative amount of solid substance under the stress. The deviations from the strength-specific gravity regression must be due to some property of the solid material, either its arrangement (size, shape, and distribution of the cells) or its internal structure and constitution.

The great bulk of coniferous wood is made up of fibers the length of which is about 100 times the breadth. The end walls

[1] The term "southern pine" refers to the hard or yellow pines native to southeastern United States, the most common species of which are longleaf pine, *Pinus palustris* Mill., shortleaf pine, *P. echinata* Mill., and loblolly pine, *P. Taeda* L. These woods are not distinguishable anatomically though there are statistical differences in specific gravity and growth-ring measurements. The last two are frequently designated together as "commercial shortleaf pine."

are tapered to points so that all but an insignificant amount of the solid material occurs as vertical tube walls. A cross-section of these tubes, then, presents an approximate map of the volumetric proportion of solid to air space, and the ratio *cell-wall area ÷ wood-section area* may be regarded as equal to the ratio *specific gravity of wood ÷ specific gravity of wood substance:*

$$\frac{\text{cm.}^2\text{(sub.)}}{\text{cm.}^2\text{(wood)}} = \frac{\text{cm.}^3\text{(sub.)}}{\text{cm.}^3\text{(wood)}} = \frac{\text{gr./cm.}^3\text{(wood)}}{\text{gr./cm.}^3\text{(sub.)}}$$

When a stress is applied to a cross-section of a wood specimen (stress parallel to the fibers), it can be referred to the solid material by multiplying it by the ratio, *sp. gr. substance ÷ sp. gr. wood:*

$$\text{kg./cm.}^2\text{(sub.)} = \text{kg./cm.}^2\text{(wood)} \times \frac{\text{gr./cm.}^3\text{(sub.)}}{\text{gr./cm.}^3\text{(wood)}}$$

And, since sp. gr. of wood substance may be considered as constant, an index of the strength of the wood substance may be had in the quotient, *strength of wood ÷ sp. gr. of wood.*

In studies of the strength of wood different methods of eliminating specific gravity have been used by various workers under different designations. Botanists investigating the mechanical systems of plants (Schellenberg, '96, Sonntag, '03, Ursprung, '06) referred stress to the cell walls by making camera-lucida drawings of the cross-sections of the specimens, and measuring the areas of the walls and the lumens to obtain the ratio of substance to wood.

Kollmann ('36) reports the use by Monnin in 1919 of a quality index for judging wood for airplane construction:

$$\text{"Statische Kennzahl, } I_s = \frac{\sigma_{-B}}{100 \cdot r_{15}}\text{"}$$

where σ_{-B} is the compression strength in kg./cm.^{2}, r_{15} is the specific gravity of the wood at 15 per cent moisture content in

gr./cm.^{3}, and I_s is the index in kilometers. Kollmann also compared wood with other materials in tensile strength by the factor "Reisslange" (breaking length), *tensile strength ÷ specific gravity.* He attributed this term to von Reuleau in 1861, who evidently used it as a measure of the strength of wires and threads. It represents the length a strand can attain without breaking under its own weight in tension, all the terms being in the metric system. Rothe ('30) converted his strength data to those of strength of cell-wall substance by multiplying the compression stress by the ratio *sp. gr. wood substance ÷ sp. gr. wood,* and gave essentially the same justification given above. Trendelenburg ('31) compared European and American Douglas fir by the quotient, *strength ÷ sp. gr.* Lassila ('31) and Jalava ('34) used the same fraction, calling it the "Janka quotient," in comparing pine from different forest types in compression strength. Markwardt and Wilson ('35) used the same quotient to compare compression strength of a very light species and a very heavy one and called it "Specific Strength." In relating strength to cell-wall structure Pillow and Luxford ('37) used as the dependent variable the "ratio of strength to specific gravity," in which the specific gravity was raised to a power expressing its empirical relationship to the particular strength property involved. The curvilinear strength-density correlation provided here takes the regression line through the zero-zero origin, but in the range of the concentration of data the exponents used give very nearly a straight line, so that this ratio is not incompatible with the stress-density theory given above.

Berkley ('34) tended toward eliminating specific gravity in his study of strength properties by choosing for analysis the specimens deviating most from the regression of strength over specific gravity. Clarke ('36) employed the same method when he compared "outlying" specimens in the same specific gravity range.

GROSS STRUCTURE

It is generally known that strong wood in conifers is associated with an optimum growth ring width for each kind of wood

and with a high percentage of summerwood. Thus Wilson ('34), speaking of the quality of wood for structural timbers, states:

> Selection for rate of growth requires the number of annual rings per inch on the end of the piece to be within a specified range. Selection for density imposes in addition to the limitations of growth the requirement of a minimum percentage of summer wood.

Structural grading rules for coniferous woods generally follow these principles.

(a) Growth Ring Width.—This is commonly regarded as only indirectly affecting strength through specific gravity. The optimum ring width for strength appears to be the optimum for specific gravity. Thus, Markwardt and Wilson ('35) illustrate the effect of rate of growth in conifers with a graphical correlation of specific gravity over rate of growth, showing optima for different stand types of redwood near twenty rings per inch. Trendelenburg ('31) shows that specific gravity and strength have the same optimum ring width for Douglas fir. Paul ('30) further connects growth rate with specific gravity and with percentage of summerwood:

> Both very wide and very narrow annual rings in conifers usually contain a larger proportion of the spring-wood layer, so that in these species wood representing either extreme of growth may be low in specific gravity.

Alexander ('35) has given for Douglas fir average figures and graphical correlations of compression strength and specific gravity over rings per inch on the same chart with superimposed ordinates. The straight-line curves for the dependent variables are both somewhat irregular but they have nearly the same irregularities. This seems to substantiate the assumption that specific gravity is the controlling factor here (fig. 1). The present writer has plotted Alexander's average data as strength per unit density over rings per inch in fig. 2, the new data representing the average crushing strength divided by the average specific gravity for each rings-per-inch class. The result seems to indicate that only part of the relation between ring width and strength is due to specific gravity and that some other factor affecting strength varies fairly regu-

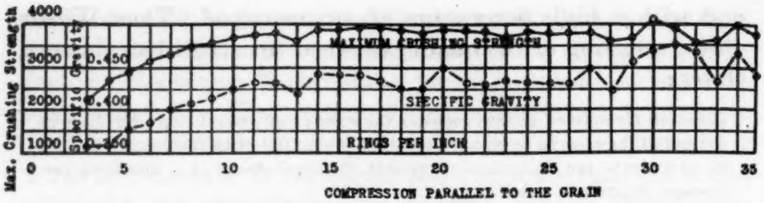

Fig. 1. Average compression strength parallel to the grain and average specific gravity plotted over rings per inch for green Douglas fir. (After Alexander, '35.)

larly with growth rate. Since the original material was chosen to be truly representative of "every varying condition of structure from pith to bark and from stump to top," the low strength on the rapid-growth end of the curve is probably partly due to the presence of wide-ringed material such as "compression wood" and wood near the pith, which are known to be abnormal in strength properties.

Koehler ('38) indicates that wide-ringed loblolly pine ranks low in most strength properties for its specific gravity and has certain resemblances to "compression wood." He shows graphically the high frequency of wood of high longitudinal

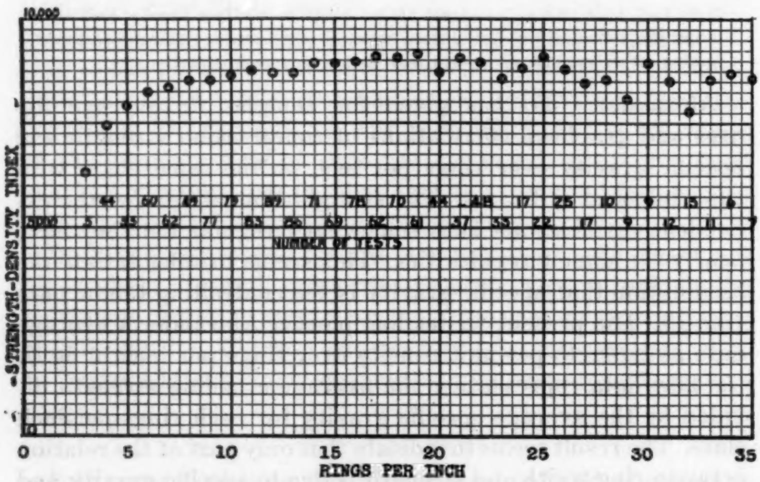

Fig. 2. Strength-density index (average compressive strength in lbs./in.² ÷ average specific gravity in gr./cc.) plotted over rings per inch for the data of fig. 1.

shrinkage among wider-ringed specimens of loblolly and slash pine. This feature is typical of "compression wood."

(b) Percentage of Summerwood.—The visual estimation of density of coniferous wood is based on the fact that summerwood is more dense than springwood. Percentage of summerwood is a good criterion of specific gravity only in so far as its density is constant. Grading rules control this factor only in specifying that the color of the summerwood be dark. It is certain that there are variations in density of summerwood within any species and that the relative areas of springwood and summerwood cannot be used as true criteria of mechanical properties unless they are qualified by specific gravity. With wood density and percentage of summerwood constant, the distribution of solid wood substance between springwood and summerwood may vary. This would reflect variations in fiber measurements (cell diameter and wall thickness) which perhaps affect the strength properties of the individual cells. At least, we can conceive that two tubes of the same material, length, and cross-sectional wall area, but with different diameters and wall thicknesses, would react differently in end compression. Clarke ('33) made a correlation study of strength, specific gravity, ring width, and percentage of summerwood in ash. Since with specific gravity constant, strength decreased with an increase of summerwood, he concluded that the thickness of the walls of the summerwood fibers is an important controlling factor.

The empirical nature of the previous research on the mechanical properties of wood is attested by the dearth of literature on the strength of isolated springwood and summerwood. In the first part of the century botanists considered this aspect, but they worked with what is regarded as abnormal wood and the methods of testing were not well controlled. Sonntag ('03) reported on the tensile strength of spruce specimens of 1 mm.-square section in "Rothholz" ("compression wood") and "Weissholz" (white wood, wood diametrically opposite "compression wood" in the stem). Although his tests were few and widely varying, summerwood was found to be stronger than

springwood in tension parallel to the fibers in both types of wood, even basing the stress on cell-wall area. Ursprung ('06) reported the same relation for springwood and summerwood of the upper and lower sides of branches of spruce in both tensile and compressive strength. Von Schrenk ('28), testing small beams of southern pine, found that springwood had roughly half the maximum fiber stress of summerwood. Forsaith ('33) used small beams (2″ × .09″ × .09″), each with a single layer of springwood and one of summerwood. He reported bending strength and stiffness when these layers were in different positions (springwood up, springwood down, and springwood at side.) He concluded that summerwood is stronger in compression than springwood is in tension, and that "the difference between the ultimate strength in tension and compression is greater in springwood than in summerwood," also, that "stiffness is more or less controlled by the summerwood."

It may be concluded that there is a need for a study of growth rate and strength-density which carries the controls down to measurements of cell diameters and cell-wall thicknesses in springwood and summerwood of carefully chosen normal wood.

(c) Heartwood and Sapwood.—In the wide testing experience of the Forest Products Laboratory (Markwardt and Wilson, '35) "no effect on the mechanical properties of most species due to change from sapwood to heartwood has been found." The structural features do not change in the process, but the heartwood is infiltrated with added materials which may be dissolved out with apparently no effect upon the wood substance. Luxford's ('31) tests on species high in heartwood extractives indicate that heartwood has some strength advantage, especially in compressive strength parallel to the grain.

Where specific gravity is to be rigidly controlled it should be remembered that extractives add to the weight of heartwood, and this may be considerable in resinous species. Berkley ('34) was able to improve his relationships of strength over specific

gravity for southern pine by correcting specific gravity for benzol extractive.

HISTOLOGY

Differences in the kinds of cells, their proportions and their arrangements, may be expected to explain partially differences in strength properties among woods of different anatomical types. Likewise, variations in amounts of different cellular elements might cause variations in the strength-density relationship of a group of specimens of the same anatomy. In elucidating the causes for brashness in wood Koehler ('33) gave deficiency of wood fibers[1] (oak) as one of the reasons for deviations in the relation of per cent of summerwood to toughness. In this case there would be an excess of wood parenchyma, a cell type that differs from the wood fiber not only in the relation of wall thickness to cell diameter but also in morphology.

Coniferous woods are simple in that the vertical elements are of only two general kinds, parenchyma cells and tracheids, and the latter predominate. In the pines, wood parenchyma is normally confined to one or two layers of thin-walled flattened cells surrounding resin canals. Vertical resin canals are intercellular spaces without walls, and so do not affect the strength of wood substance except as they account for the presence of parenchyma. Their effect on the strength of wood is limited to an interruption of the solidity of the tracheid mass. Berkley ('34) found the diameter of resin ducts in southern pine varying from 0.19 mm. to 0.25 mm. The cross-sectional area was 0.66–2.5 per cent, and the variation between strong and weak specimens was evidently not significant.

Wood rays certainly must play an important role in the distribution of stresses in wood, but there is little definitely known about this. They exclude part of the weight of the wood from participating in efficient axial stress resistance and they cause deformation of the contours of adjacent tracheids. On the other hand, they form a very effective lateral bracing and

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[1] The term "wood fiber" refers to a particular type of cell found in hardwoods. The term "fiber" when used alone refers to fibrous cells in general.

seem to make up for the weaknesses that might be due to a lamellar (springwood and summerwood) structure. In end compression tests, wood fractures quite regularly in a sloping radial plane. Berkley ('34) attributed this directly to the rays and reported that Thil in 1900 and Fulton in 1912 agreed with him. Jaccard ('10), Robinson ('20), Forsaith ('33), and Bienfait ('26) each observed that initial failure is not associated with the rays. Iwanoff ('33) found that the fibers bend most frequently at the rays, but that there is another more angular type of fiber failure that is not dependent upon the rays. Bienfait ('26) saw no difference between radial and tangential walls as to indications of initial compression failure. He suggested that the plane of fracture is indirectly caused by the stiffening effect of the wood rays against gross fracture in a tangential plane. Koehler ('33) regards the rays as ineffective in determining resistance to toughness. Among Berkley's ('34) outlying specimens of southern pine, in the graphical correlation of compressive strength with specific gravity, the weaker specimens averaged about one per cent more of total area occupied by resin ducts and wood rays than the stronger specimens. He concluded that the larger number of wood rays and resin canals contributed to the weakness of the material, especially the wide-ringed, short-fibered wood in the first few rings near the pith.

Fusiform rays (containing horizontal resin canals), also measured by Berkley, varied from 0.053 to 0.075 mm. in width and from 0.35 per cent to 1.61 per cent of total area. He regarded them as effective in causing compression failures.

It seems reasonable that the rays may play two opposing roles in the resistance to stress in wood, which may be partially compensating.

TRACHEID MORPHOLOGY

Forsaith ('26) stated that tracheids occupy 90 per cent of the stelar volume in conifers. Berkley ('34) showed that resin ducts and rays occupy roughly 10 per cent of the cross-sectional area in southern pine. Since the ray and parenchyma cells have much thinner walls than tracheids, it is certain that tracheids

constitute well over 90 per cent of the weight of this type of wood. It would seem that an explanation of the large strength-density variations must be associated with this element.

The tracheid is defined as an "imperforate cell with pits to congeneric elements bordered" (Record *et al.*, '33). In southern pine its length is about 100 times its greatest breadth. It varies in cross-section from approximately isodiametric, large-lumened, thin-walled in springwood, to tangentially flattened, small-lumened, thick-walled in summerwood. Normally these cells fit closely together in well-defined radial rows. The cells of "compression wood" are more or less rounded in cross-section, have larger lumens in summerwood and thicker walls in springwood than normal wood, are less regular in arrangement, and may have intercellular spaces among them at the corners. The walls of normal tracheids are parallel except near the ends where they taper to a point in summerwood or to a radially oriented wedge in springwood. The ends may be more or less curved radially. Abnormal cells may have irregular curvature throughout the length, which, according to Berkley ('34), is associated with specimens weak in end compression.

The length of tracheids varies considerably among specimens of the same wood. Short tracheids are known to be associated with "compression wood" and the wide-ringed material of the first several years' growth. Berkley ('34) found the average length of tracheids in his southern pine specimens to be between about 2.5 mm. and 5.0 mm. However, the average length of tracheids for his strongest and weakest woods was about the same. Koehler ('33) saw no relation between tracheid length and toughness and attributed this to the fact that the fibers are cemented firmly together and a slipping between fibers is not involved in failure. Sonntag ('03) found considerable difference in the range of tracheid length between "compression wood" and "tension wood" but did not attribute the low tensile strength of "compression wood" to this. Since stresses parallel to the fibers actually cause failure in diagonal shear and since the contour of the fiber is not uni-

form throughout its length, it is probable that the above conclusions are valid in spite of the fact that some types of weak wood have short fibers.

Bordered pits are confined to the radial walls of tracheids almost exclusively. A bordered pit is defined as "typically, a pit in which the cavity becomes abruptly constricted during the thickening of the secondary wall" (Record *et al.*, '33). Viewing an isolated tracheid the bordered pit appears as a saucer-shaped depression on the wall with a small circular opening at its center, the canal. The pits of contiguous tracheids are paired so that the depressions form a lenticular space, the chamber. In springwood the whole wall takes the form of the chamber and has about the same thickness throughout except for a rounding off at the canal. In springwood of southern pines the chamber (marking the border) extends to half or more the width of the cell. In summerwood the border and canal are smaller, the chamber is shallower in the wall surface, and the canal extends from the outer aperture (at the chamber) to the inner aperture at the inner wall surface. Usually the inner aperture is more or less lens- or slit-shaped. Bordered pits are much less numerous in summerwood than in springwood.

Jaccard ('10) and Tiemann ('06) regarded the bordered pits as points of weakness in compression, but Robinson ('20), Bienfait ('26), and Forsaith ('33) did not agree. Forsaith observed that both compression and tension failures avoid the pits and that the line of fracture runs around the border rather than through the canal. Koehler ('33) regarded bordered pits as stronger than other parts of the wall because of concentric fibrillar arrangement in the overhanging wall. Sonntag ('03) found larger bordered pits and especially longer pit slits in "compression wood" than in "tension wood" of spruce branches and assigned this as a cause for lower tensile strength of "compression wood."

Each conifer tracheid comes in contact with a wood ray at a number of places in its length. At these crossings the tracheid wall is indented or the whole cell is bent to conform

to the lenticular cross-section of the rays. This bending of the fiber wall has been blamed for a lower resistance of the wood to axial compression stress. In the ray crossings the pits to the ray parenchyma cells have large canals, and the reduction in wall section may be considerable. Forsaith ('33) observed that the line of fracture (tension?) may shift slightly to take advantage of these pits.

It has been shown that there are several features of the architecture of the individual tracheid the variation of which may have an effect on the strength of wood as a whole. The study of the parts played by these features is complicated by the fact that the fibers are cemented together with a material which seems to hinder the fibers from acting individually. Thus from his microscopic examination of fractures in small bending specimens, Forsaith ('33) concluded that:

> . . . the plane of fracture follows the area of maximum stress, and that anatomical inequalities in wood do not deflect the line of cleavage more than a few microns. Furthermore, where fracture does jump from cell to cell, there seems to be no specific reason why it should depart from the middle lamella line at this point. All things considered, it would appear that the minute structure of the wood plays a relatively unimportant part in locating failure, in comparison with that determined by a concentration of stresses in the region of maximum moment.

This may be valid for bending fractures because here the longitudinal stresses are concentrated under the loading point. And especially is it true for Forsaith's tests where one kind of stress was confined to one part of the annual ring and there was not the complication of stresses as in the whole wood where two different kinds of material are involved.

The axial compression test, too, seems to be ill adapted to the study of centers of weakness in the cell structure. Once failure takes place in a relatively small group of cells, or theoretically at a certain point on the wall of a single cell, the fracture seems to affect the neighboring cells and the progress of the effect often proceeds in a quite regular pattern without much selection of points of weakness. In axial tension fracture, however, there is little regularity, and it seems valid to assume that the pattern of fracture is determined by the points of

weakness in the individual fibers which may be associated with contour features.

TRACHEID WALL STRUCTURE

With ordinary microscopic methods fiber walls of light-colored woods (and sapwood) usually appear quite transparent and without structure. With staining, a thin outer layer may be differentiated, and under certain conditions striations and checks may be seen in longitudinal view which indicate a spiral structure. Polarized light confirms the concentric and helical anisotropy. Chemical or mechanical micro-dissection may serve to separate fine threads or fibrils from the wall. These facts have been known for nearly a century, but only recently have details been provided for even the structure of the cell wall within the range of the microscope. Below microscopic range an hypothetical crystal-like unit suggested by Nägeli in the middle of the last century, and named by him the "micelle," has been widely accepted. Since then the concept has been carried over into the field of colloidal chemistry where the unit is often designated as one type of crystallite. Although great advancement has been made in the understanding of the sub-fibrillar structure of the plant cell wall since Nägeli's time, the micelle is still without exact definition.

The recent work by I. W. Bailey and his associates on the cambium and its derivative tissues has yielded the most lucid exposition yet available of the visible structure of the conifer tracheid. Kerr and Bailey ('34) gave the results of their optical and chemical differentiation of the lamellae of normal woody fibers and offered a terminology to clear up obvious discrepancies in designation by earlier workers. This terminology is used in the present paper. In order from the outermost layer the terms are: middle lamella (or intercellular substance), cambial (or primary) wall, and secondary wall with its outer, central and inner layers.

Between contiguous mature fibers is a single layer of optically anisotropic material known as the middle lamella. It is quite thin except between the rounded corners of the tracheids,

and is difficult to distinguish from the true primary wall layers of the two adjacent cells because all three are highly lignified. It has been shown to contain, besides lignin, substances which are dissolved by solvents for polyuronides.

The outermost true layer of the cell wall is designated the primary or cambial wall. This is the original wall of the cambial initial, and though very thin and highly lignified it has been shown to have retained a true cellulose structure and also some of the original polyuronides of the cambial initial. The cellulose in the primary wall is shown to have positive birefringence in both transverse and longitudinal sections. Bailey ('38) has observed a wide variety of structural patterns which are all porous but coherent. His figure suggests the "folienstruktur" of Frey-Wyssling ('35), who attributed it to all primary meristems. In this structure the cellulose is layered in the plane of the cell wall but is not oriented in a direction perpendicular to this plane. Because of its thinness and lack of orientation the primary wall may act mechanically with the true middle lamella as an amorphous substance, the binder between the cells.

Next within the primary wall lies the secondary wall. By its optical activity it is seen to consist largely of well-oriented cellulose, though it is usually more or less lignified (Bailey and Kerr, '35, '37), with the lignin constituent variously distributed. Normally in tracheids the secondary wall is divided into three consecutive layers according to the fibrillar orientations: (1) a thin layer (next to the primary wall) with the fibrillar orientation in a relatively flat helix (45° to almost 90° with the cell axis); (2) a thick central layer with fibrils in a relatively steep helix (almost 0° to 45° with the cell axis); and (3) a very thin inner layer with fibrils in a more or less flat helix. The inner layer is least well known though its anisotropy has been shown by birefringence in both longitudinal and transverse sections of the wall.

The fibrillar structure of the central layer may often be detected with ordinary microscopic methods. It is evident from striations and checks in the wall and from the threads or fibrils

of cellulose which can be dissected mechanically (Seifriz and Hock, '36, and others) and chemically (Ritter, '35, and others). The outer layer may also be seen to be made up of thread-like fibrils if it is viewed apart from the central layer. Although Ritter ('35) has shown fibrils to occur as threads as long as 230 μ, Bailey and Kerr ('35) maintain that the cellulose of the central layer occurs in a continuous system of heterogeneous elongated and anastomosing "complexes." They state:

> The form and size of the fragments which may be dissected from the secondary wall are clearly dependent upon the structural pattern of the matrix of cellulose and upon the type and severity of the chemical and mechanical treatments to which the material is subjected.

It is feasible to agree with them that the wide variety of proposed "ultimate units" of cellulose may be due to differences in chemical technique. Their concept of the fibrillar structure includes the interweaving of an anastomosing system of non-cellulosic materials within the interstices of the cellulose structure, and they have shown photographic evidence of similar patterns obtained by treatment with lignin solvents and with cellulose solvents. These chemical patterns will be discussed in the next section.

Bailey and Vestal ('37), with a method of forming iodine crystal aggregates within the interstices of the cellulose structure, have presented convincing evidence of the structural orientation in the outer and central layers of normal conifer tracheids. Their survey indicates that the angles of orientation are not specific for species of wood. They regard as the normal condition in summerwood an axial orientation of the central layer and a helical one for the outer layer; in springwood the central layer is helical and the outer layer is perpendicular to the axis. These patterns were not found to be strictly confined to each part of the annual ring. The angles of orientation may vary from cell to cell, so that combinations of axial central wall with transverse outer wall and helical central wall with helical outer wall were of common occurrence.

Regarding changes in orientation within the central layer, Bailey and Vestal ('37) state:

The orientation of the fibrils may fluctuate, at times, in the successively formed growth rings[1] or lamellae of the central layer, but pronounced shifts are of relatively infrequent occurrence in the tracheids of conifers. Regularly recurring changes from right-handed to left-handed helixes or *vice-versa*, such as are hypothesized by various investigators, are rarely, if ever, encountered in the central layer of coniferous tracheids.

Scarth, Gibbs, and Spier ('29), Lüdtke ('31), and others have described the secondary wall of fibers as made up of as many as ten or more concentric laminae, the direction of the slope of the fibril axis alternating with each layer, and with these laminae constituting separate cellulose structural systems separated by layers of amorphous material. Ritter and Chidester ('28) gave photographs of elm fibers in which the sleeve-like lamellae have been made to telescope by chemical treatment, and they attributed this structure to wood fibers in general. Bailey and Kerr ('35) ascribed it to only certain types of cells. They concluded, after a wide survey of gymnosperms and angiosperms, that the secondary wall of normal tracheids, fiber-tracheids, and libriform fibers consists of but three layers of varying orientations (as indicated above), and further that the central layer consists of a continuous structural system (the cellulose matrix with an interwoven noncellulosic structure).

The iodine-crystal technique of Bailey and Vestal ('37) has given detail in fibrillar deviations within a given wall layer. The linear fibrillar structure of the outer layer seems to be discontinuous at the border (chamber) of the bordered pits, and within the border the fibrils are in concentric orientation. The fibrils of the central layer, however, seem merely to be deviated around the pit canal from their normal course. This deflection is given by Bailey and Vestal as a reason for the radial walls in springwood having a greater fibrillar angle than the tangential walls. Since the central layer normally makes up the greater part of the tracheid wall, its properties are ordinarily designated as those of the entire cell wall.

Preston ('34), in a quantitative study of the organization of

[1] This is the chemical pattern which will be discussed below.

the conifer tracheid cell wall, noted that the fibrillar inclination is greater on radial walls than on tangential walls and that the angle on the radial wall varies between growth rings as a function of average length of springwood tracheid in the ring and of average radial breadth. Maby ('36), using wall checks and pit slits (elongated inner orifices of bordered pits common in summerwood) as indications of structural orientation in tracheids, found for *Tsuga heterophylla* summerwood good positive correlation between angle of inclination with the fiber axis and radial lumen width. Wall thickness did not have good correlation with the angle. This worker also observed that in hemlock springwood fibrillar orientation of the radial wall at the pits is not a good criterion of the orientation in the clear, the average angle for pit slits being about twice that of the checks in the clear. Further, he observed that the orientation at ray crossings was little more than half the angle in the clear. It appears that orientation in springwood tracheids is quite variable and that a true average would embrace several widely different morphological conditions.

That orientation of the fibrillar structure is important in determining strength of fibers is not difficult to conceive; especially is this true in consideration of tensile stresses. It is known, for instance, that the very strong bast fibers of ramie and flax have good fibrillar orientation; that is, the fibrils are almost parallel to the fiber axis.

That the cellulose fibrils of wood (matrix of elongated complexes) are more resistant mechanically than the non-cellulose constituents (interwoven system of isotropic material) may be supported by a brief discussion of the sub-microscopic structure of wood substance. X-ray, polarized light, and swelling technique have demonstrated that the cellulose is oriented parallel to the fibril axis. X-ray diffraction analysis has further shown that the cellulose molecule consists of long chains of anhydroglucose units. The length of the chains and their combinations into structures up to the limits of microscopic visibility have not yet been agreed upon. Meyer ('28) thinks that the chains are about 60 glucose units long, very

strong by reason of primary valence bonds between the glucose units, and that they are held together in bundles (micellae) by secondary valences the high force of which he attributes to the size of the large chain-like molecule. Further, the unsatisfied secondary valences of the outer chains of the micellae constitute a force by which the micelle may adhere to other micellae or may adsorb other molecules. Astbury ('33) and others view the micelle not as a unit structure but merely as a concentration of molecular chains of varying lengths some of which may extend to other micellae forming a continuous cellulose system of indefinite pattern. This concept seems well supported by several different types of physical measurement (Stamm, '36) which give molecular chain lengths far exceeding the unit micellae that have been hypothesized. Below the size of the fibril the problem of the strength of wood is in a theoretical field, but the rapidly developing study of colloidal chemistry may be expected soon to yield methods of obtaining significant submicroscopic data. It must be borne in mind that even if all the factors in microscopic range were controlled there might exist within the fibril structural variables of importance to strength. The non-cellulosic constituents of wood are amorphous, i.e., have no organized molecular forces, and as such must be regarded as secondary in determining strength properties.

High fibrillar angle occurs with low strength in both compression and tension in "compression wood." Pillow and Luxford ('37) have plotted three different strength-density ratios over the sine of the average angle of slope of fibrils for eight specimens of "compression wood" and six specimens of normal wood of air-dry loblolly pine. The average angles were weighted on the basis of springwood-summerwood proportions. The normal wood specimens fell between 14° and 16°, while those of "compression wood" had a range of about 26° to 34°. In spite of the small amount of data and the wide gap in slope of fibrils between normal wood and "compression wood," there appear to be good graphical relationships. Maximum crushing strength and modulus of elasticity in bending

vary almost linearly through "compression wood" to normal wood. Modulus of rupture[1] seems to vary linearly in the "compression wood" region, but the specimens with average angle of 26° appear to be almost as strong as normal wood. This would indicate that ultimate bending strength is not affected until the average fibrillar angle reaches about 25° where it drops off rapidly with increasing angle. Of the three strength properties shown here, modulus of elasticity in bending, on a density basis, is the most sensitive to changes in fibrillar angle and appears to have the least dispersion from the regression line. The bending-strength relationship is the most inexplicable and is also the most unsatisfactory statistically.

The value of using angle of fibrillar orientation for predicting strength may be roughly conceived by comparing the dispersion in the graphical correlation described above, where strength is made dependent upon both specific gravity and fibril angle, with one in which only specific gravity is used as a criterion. The above relationship for compression strength has a dispersion range of about 2000 lbs. / in.^{2} per (gr./cc.)$^{1.25}$, which is equivalent to about 1000 lbs. / in.^{2} for the average specific gravities given in the tables for air-dry loblolly pine specimens. This may be compared with a dispersion range of about 3500 lbs. / in.^{2} as shown in Berkley's ('34) plot of compressive strength over specific gravity for air-dry loblolly pine. Even from this crude comparison and the few data upon which it is based, the fibrillar orientation angle in the central layer of secondary walls of the conifer tracheid gives promise as a quantitative criterion of strength properties of the wood in axial stresses.

It is interesting to note that fibril angle is important in axial compressive strength, in the light of microscopic evidence that cell wall fracture in compression seems to be independent of fibrillar structure. Many workers, notably Robinson ('20) and Bienfait ('26), have reported the so-called "slip lines" occurring in the walls (seen in longitudinal section) of wood fibers that have been subjected to longitudinal compressive

[1] This is a measure of bending strength.

stresses. These lines represent radially sloping tangential planes of shear much as might be expected in tubes of isotropic material which have been subjected to end compression. The angle in a radial plane which these lines make with the cell axis is about 70° according to Bienfait ('26) and Iwanoff ('33). These shear planes extend transversely or at a slight incline around the cell in the wall. They occur concentrated in the region of gross compression failure, and are more widely distributed in green wood that has been stressed than in dry. Robinson ('20) found them in specimens stressed just to the elastic limit and called them indications of initial failure. Koehler ('33) suggests that they are sometimes induced by stresses in the tree and gives their occurrence as one of the causes for brash tension failure.

Robinson ('20) observed that longitudinal tension failure of the fiber wall occurs in planes parallel to the pit slits in the summerwood of normal spruce, but for "brittle" spruce and for a number of harder woods, including pitch pine, the wall fracture is transverse, resembling the compression fracture. Koehler ('33) has shown tension fractures in cells at least partially following the fibrillar orientation, indicating planes of weakness between the fibrils. He concludes that there is a relation between fibril angle and tensile strength, thus:

> Obviously the fibrils must also break somewhere, as well as separate from each other, in order for a fracture to be complete, but the greater the slope of the fibrils the smaller will be the failure within them and the greater the failure between them. If the fibrils should make an angle of nearly 90° with the cell axis, a condition approached in some hardwood vessels, then failure in tension along the grain would be almost entirely between fibrils and the resistance offered by the cell wall would be relatively small.

With regard to regenerated cellulose products, Houwink ('37) suggests that strength may be proportional to micelle length for well-oriented material and supports this by showing that high viscosity of the solution produces strong rayon. Viscosity is thought to be dependent upon micelle length. He illustrates fracture planes for long and short micellae progressing between the micellae and transverse to their orientation. The longer micellae force the fracture line into a more

deviating and longer path than do the short ones, thus providing more area for the distribution of a given stress. This concept may be applied to the anastomosing continuous system of fibrils in natural fibers, by taking as fibril length the longitudinal distance between successive thin places (points of weakness) in the framework. Chemical dissection of fibrils indicates that some points in the framework are less resistant to solvents than others, and there is a possibility that a quantitative structural measurement may be attained through controlled chemical dissection.

The transversely oriented outer layer of fibers has generally been neglected in structural considerations. However, Sonntag ('09) suggested that the difference in the fibril angle between outer and inner (central) wall is important in the mechanism of failure under axial tension. He used as a model two wire helices, one with a flat spiral and one with a steep spiral, the latter inside the former and attached firmly to it at the ends. If this system is stretched longitudinally the inner helix is reduced in diameter more than the outer one and thus pulls away from it. This mechanism was offered as the cause of concentric discontinuities in the cell structure that lead to ultimate fracture of the wood. Thus "compression wood" would be less likely to fail between the outer layer and the central layer than normal wood, because the angle of spiral is more nearly the same in the two layers. However, other structural abnormalities must offset the advantages since "compression wood" is notoriously weak in tension.

The continuous micellar structure of the central layer of the tracheid as elaborated above referred to normal tracheids. Bailey and Kerr ('35) state:

> Conspicuous discontinuities are, however, of not infrequent occurrence in the peculiar tracheids of "compression wood," in so-called gelatinous fibers, in certain types of bast fibers, and in sclerids. This is due to narrow layers of *truly isotropic* material which contain little if any cellulose.

Radio-helical discontinuities or "checks" in the fiber wall are conspicuous and well known in "compression wood." Hartig ('01) illustrated this type of tracheid in some detail. In cross-

section the checks open into the lumen and extend nearly across the central layer. They may branch dichotomously for a short distance near the outer layer. The checks follow the helical orientations of the fibrils, forming radio-helical plates. Hartig also illustrated "tension wood" and showed radial checks which are less profuse and extended from the outer border of the central layer a short way into it. Such checks were not found in fresh wood and were attributed to drying. Another anomalous feature shown for "tension wood" is the occurrence of spiral thickenings on the inner face of the secondary wall (tertiary wall), especially in summerwood (spruce). Hartig also mentioned an extraordinary development of the tertiary wall (inner layer of the secondary wall). He believed this layer to be absent in "compression wood."

CHEMISTRY

A logical method of attack on the strength problems of any structure would entail an examination of the mechanical properties of the various component materials. Unfortunately the materials which compose wood are so intimately associated and apparently so heterogeneous that only general and vague contributions to their individual study can be expected from chemical considerations at present. The constituents of wood are usually grouped in three classes: (1) cellulose, (2) hemicelluloses, (3) lignin. Quantitative determination depends upon solvents used, their concentration, and exact conditions of procedure.

Cellulose is a long-chain polymer whose molecular unit is known but whose chain length is probably variable. Hemicelluloses constitute a mixture of carbohydrates some of which are associated with cellulose in the structural framework and some are not (Norman, '37). Lignin is a non-carbohydrate of unknown chemical structure, and amorphous. Koehler ('33) is of the opinion that the chemical composition of wood is relatively invariable within a species. Ritter and Fleck ('26) found that for a number of species springwood is mostly lower in cellulose and higher in lignin than summerwood. This is explained by the fact that lignin tends to be concentrated in the

"middle lamella" and that the "middle lamella" is a greater proportion of the total wall volume in the thin-walled springwood than in the summerwood. Dadswell and Hawley ('29) reported the difference in chemical composition between brash and tough specimens and between normal wood and "compression wood." Brash Douglas fir of the same density as tough wood had insignificantly greater percentage of cellulose and of lignin than normal. The measure of toughness was 276 cm.-kg. for the tough specimens and 132 cm.-kg. for the brash ones. Although the authors did not observe structural differences in the above specimens they believed that "there may be structural differences that fully account for the strength differences." Comparing normal wood and "compression wood" of Sitka spruce and redwood, they found appreciably lower cellulose content and higher lignin content in "compression wood." Here structural differences were known, but they were "not certain that they were the cause of the variations in strength properties." They also found that the springwood-summerwood relationship of the cellulose and lignin content as shown by Ritter and Fleck was reversed in the case of redwood "compression wood."

These authors (Dadswell and Hawley, '29) are not willing to agree with the concept that has been general among botanists, that lignification is always a source of strength in cellulose plant fiber, nor do they agree with Schorger whom they quote, "It is known that the amount of lignin present in a wood has no direct relation to its mechanical properties." They point out that lignin occurs in a "free condition" in the middle lamella and mixed with relatively large amounts of other material within the fiber, and offer this pertinent observation:

> Variations in the amount of lignin, therefore, have entirely different effects on the strength, depending upon where the variation occurs. Increased lignin content in those parts of the structure where it is mixed with cellulose may increase certain strength properties, while increased lignin content due to increased size of the middle lamella may decrease certain strength properties.

This concept leads us back to the more recent work of Bailey and Kerr ('35, '37). They have disclosed by the use of ap-

propriate solvents on very thin wood sections what might be called the chemical pattern of cellulosic and non-cellulosic constituents of the central layer of the secondary wall. The patterns are explained thus:

> Lamellae of varying porosity or density are due to fluctuations particularly in the number of fibrils per unit area. In other words, the fibrils are loosely aggregated in the more porous lamellae and are closely compacted in the denser lamellae. [Bailey and Kerr, '37]

In a survey of the fibrous cells of higher plants there was shown to be a wide variety of patterns made up of concentric and radial lamellae or zones of various spacing and prominence. In their later paper Bailey and Kerr ('37) have elucidated the distribution patterns in the conifer tracheid which vary from the normal condition to that of "compression wood" as extremes and show intergrading forms. In the broad central layer of the secondary wall of normal tracheids the laminae of varying density are relatively narrow and arranged concentrically, though a weak radial pattern of density may be seen as an undertone. There are no discontinuities in the cellulose system. In the intermediate forms the radial pattern gains prominence, and there may appear to be superimposed concentric and radial distribution. "The wall may exhibit a prevailingly and finely radial pattern." The fibrillar system may still be continuous though "it tends to develop radio-longitudinal cracks in drying. . . ." In the extreme case of "compression wood" the broad inner layer is "composed of coarse, radio-helically oriented plates" which are separated by actual discontinuities in the cellulose system. "Furthermore, the broad inner layer is separated from the narrow first-formed layer of the secondary wall by an isotropic layer of non-cellulosic composition." This last type of wall has no detectable inner wall comparable to that of normal tracheids (Bailey, '38).

Although the chemistry of the cell wall is too obscure for an exact structural analysis, the above information on the distribution of the two main classes of materials, combined with a knowledge of the longitudinal orientation of the wall, should lead to an understanding of the processes of strength resist-

ance in the cell. This follows on the assumption that cellulose is rigid and the non-cellulosic material furnishes planes or regions of weakness. Regarding planes of structural weakness, Bailey ('38) says:

> The more important planes of cleavage in native cellulose are of two types: (a) those that are determined by the visible differences in density and porosity, and (b) those that are governed by submicroscopic factors. The former planes are oriented parallel to the long axis of the porosities and therefore of the fibrils and are effective in dissecting the wall into concentric or radio-helical layers and into elongated aggregates of fibrils. The latter are significant during the chemical dissociation of cellulose into fusiform bodies and other small fragments.

He suggests as a possible indication of submicroscopic planes of weakness the angular ends of hyphal chambers of some fungi working within the cell wall. The cavities are oriented parallel to the fibrils, and the enzyme action takes place on planes corresponding to this orientation and on planes at an angle of 20–25° to this axis without respect to the more minute fibrillar organization. This angle corresponds to that of the planes of action of strong hydrolyzing reagents which dissect fusiform bodies from the wall, and also to that of planes of acetylation of cellulose fibers illustrated by other workers. Whether these planes of chemical action are significant in mechanical dissection is not known. There is a possibility that the saw-tooth tension fracture of the fiber wall that is sometimes observed (Robinson, '20) may be associated with this. In this type of fracture one side of each tooth represents a separation between the fibrils; the other makes an acute angle to it.

MOISTURE CONTENT

The increase of all strength properties due to drying wood substance from the green or saturated condition is pronounced. The theoretical moisture content of the wood at which the fiber walls are saturated and where no free water occurs in the cell spaces is known as the "fiber-saturation point." This concept was put forward by Tiemann ('06). The practical determination of the point was made by plotting the logarithm of a strength property over the moisture content of the wood and

marking the intersection of the straight line representing changing strength values with the horizontal line representing green strength.

The intersection point varies insignificantly for different strength properties and for different specific gravities of the wood, but is considerably different among different species. Wilson ('32) found a variation from 20 to 28 per cent moisture content within a small number of species. In listing these species by progressive fiber-saturation points those of similar structure were found to be grouped.

The suggestion from this listing is that wood structure of different types, even within a single species, may have different fiber-saturation points or intersection points. [Wilson, '32].

Intersection points may also be obtained from the relation of moisture content to other variables. Wilson found the electrical-conductivity intersection point consistently higher for different species than those obtained by strength measurements, and much less variable. The discrepancies between the two methods are "possibly due to the effect of size and arrangement of elements of the wood structure on the intersection point." It might be added here that the nature of the cell wall must have great influence in determining the intersection point for strength, since the factor actually involved is that moisture content at which the wood substance starts to become more coherent.

Wilson points out that there are two factors involved in the strengthening of wood by drying, (1) the strengthening of the material, and (2) the increase in "compactness of the wood structure" due to change in volume. It is interesting to note in this connection that although the intersection points obtained from strength data agree fairly well with those from shrinkage data, the moisture contents at which shrinkage is first detectable are consistently higher than the first signs of strength increase. This indicates that the mechanism of stiffening lags behind that of shrinking.

The parameter, K, expressing the slope of the line representing the relationship of strength to moisture content below

fiber-saturation point, varies not only among species but for different groups of specimens within a species. It is not associated with specific gravity. Its wide variability among different strength properties is illustrated by Markwardt and Wilson ('35), who have tabulated a number of strength properties with the average change in strength values in terms of per cent for each 1 per cent change in moisture content. Some of these increments for spruce are: modulus of rupture, 4 per cent; modulus of elasticity (static bending), 2 per cent; maximum crushing strength parallel to the grain, 6 per cent; shearing strength parallel to the grain, 3 per cent; tension strength perpendicular to the grain, 1.5 per cent. Kollmann ('36) has published comparable figures for Swedish pine: tensile strength parallel to the grain, 3 per cent, and axial compression (crushing) strength, 4 to 6 per cent.

Pillow and Luxford ('37) found that the strength of "compression wood" does not increase so much in drying as that of normal wood. Among the properties they studied, modulus of elasticity and tension parallel to the grain were exceptional in that their proportional change on drying was not significantly different in the two types of wood. The authors believed that the evidence was inconclusive in the case of tension, due to the insufficient number of tests.

Excessive longitudinal shrinkage is typical of "compression wood," which is known to shrink considerably less than normal wood in transverse directions. The resultant effect, moreover, is a reduced volumetric shrinkage. Hartig ('01) gave an average volumetric shrinkage of 11.545 per cent for "Rothholz" of spruce as against 14.55 per cent for "Weissholz" from the same stem. Trendelenburg ('31) found 8.88 per cent volumetric shrinkage for "Druckholz" of Douglas fir and 10.25 per cent for normal wood. Pillow and Luxford ('37) reported a slightly excessive equilibrium moisture content for "compression wood." In other words, air-dry "compression wood" contains slightly more moisture than normal wood under the same conditions. The difference, from their table of

air-dry properties, amounts to about 0.5 to 1.0 per cent moisture content. The above data indicate that the strength properties of "compression wood" below fiber-saturation point may be abnormal not only because of inherent structural differences but also because of abnormal moisture relations (colloidal properties).

With regard to the mechanism of increase in strength on drying, Stamm ('36) stated:

> The strength of a swollen fiber, in general, increases upon drying. This is explained on the basis of the secondary valence forces between micelles, which in the swollen condition are partially satisfied by mobile water, being brought together on drying and thus satisfying each other. This phenomenon is well illustrated in wood.

He cited the experiments of Lüdtke, in which the tensile strength of regenerated cellulose was found in different liquids:

> In such dry, non-swelling liquids, as benzene, the tensile strength is the same as it is in air. Liquids, such as water, glycerine, and formamide, that cause swelling result in considerable decrease in tensile strength of the fibers. Such liquids as dry ether and alcohol, which have a tendency to remove water from the fibers, cause an increase in the strength of water-swollen fibers.

Russell, Maass and Campbell ('37) show that the strength of paper depends partly upon the area of contact between the fibers. Beating the pulp increases fibrillation, increasing the chances of contact and the strength of the paper. These bonds are held to be purely physical, and are shown to be affected by drying. The tensile strength of paper was increased from 0.69 to 7.28 kg. in drying. The same paper tested in the presence of methyl alcohol sustained 2.32 kg.; in ethyl alcohol, 4.63 kg.; and in propyl alcohol, 5.77 kg. These differences were given as examples of different degrees of loosening of the cellulose-cellulose bond. This suggests a careful reconsideration of the effects of extractives upon the strength of wood.

These workers have offered a theory for the mechanism of drying of cellulose. Although cellulose is not soluble in water, the glucose units of the cellulose chain would be soluble in the regular glucose solvents if they were free. Due to this, cellulose

has "surface solubility" in water. Removal of the water causes crystallization bonds to be made between the surfaces of adjacent cellulose crystallites or single chains. The surfaces are drawn together by surface tension and internal liquid tension, and this constitutes a deformation in the structure.

> Portions of the solid structure brought into contact by such deformations may become bonded together by recrystallization, if the liquid is one that can form such "surface solutions" as were earlier described. Such is the case with cellulose and water. [Russell, et al., '37.]

The above conception of the effect of moisture upon the structural cellulose of natural fibers seems valid, though it may serve as only part of the picture of the mechanism in wood where at least two other broad classes of substance are present. Here there must be secondary valences or "surface solution" bonds between cellulose and other constituents, which may not be affected by water as are the cellulose-cellulose bonds. A possibility suggested by the above theory is the drawing into orientation of some of the short-chain hemicelluloses upon drying, and perhaps their incorporation into the structural system by adsorption.

From this brief discussion of strength-moisture relations it may be concluded that the strength variations among different types of wood of the same anatomical description may not be quantitatively comparable as between green wood and wood dried to any given moisture content. Water must be regarded as a constituent of wood in its natural state, and its removal as comparable to the removal of any constituent. The course of the association of the remaining constituents during the gradual removal of one of them may vary according to the original composition. Thus when a condition is abnormal (statistically infrequent) in green wood it may be more or less so in dry wood at different moisture contents. Until abnormal types of wood can be classified and their drying constants determined, the most valid comparison of properties would seem to be based upon green material. For practical purposes two comparisons must be made, one at a moisture content representing average air-dry conditions.

III. Strength Tests and Physical Measurements

This portion of the study was executed in cooperation with the Department of Civil Engineering, Washington University,[1] and was directed by Professor A. W. Brust of that department.

For the purpose of this study the concept of strength conforms to that in accepted engineering practice. The tests follow standard procedure, with minor modifications as noted, and the results are comparable to other standard engineering studies of small clear specimens of commercial timber. Because of the difficulty of making a thoroughly representative microscopic analysis of specimens of the size used in engineering practice, special attention was given in this study to obtaining specimens of uniform growth ring structures. Uniformity could have been better obtained and the sampling made more certain by reducing the size of the strength specimens. However, as the size of the specimens is reduced there is an increase in testing errors due to undefinable stresses at points of loading and to unequal distribution of stresses by the springwood and summerwood portions of the growth rings. For this reason tests that have been designed by some botanists (Sonntag, '03, and Ursprung, '06) may not be representative of the strength conditions within trees or in large structural members, though the 1 mm.-square sections which they tested are admirably adapted to microscopic examination.

MATERIAL

The type of wood chosen to represent the conifer tracheid was dictated by its availability for personal selection of the green material and by the existence of comparable test data. Further, there were required logs of a diameter that would afford specimens without excessive ring curvature and with

[1] Mr. J. W. Graves, Jr., American Creosoting Company Fellow in Civil Engineering, collaborated in the tests, measurements, and calculations. He has used these physical data as part of the basis for a dissertation entitled "Strength and related properties of various growth structures in shortleaf pine," presented as a requirement for the degree master of science in engineering, June, 1937.

uniformity of growth. These requirements were met fairly well by commercial shortleaf pine produced in central Arkansas.

A. Species.—Commercial shortleaf pine is wood of two species of *Pinus* which are marketed without segregation, namely, shortleaf pine, *Pinus echinata* Mill., and loblolly pine, *Pinus Taeda* L. Since selection of the growth-ring structure of the material entailed a rather wide survey it was not feasible to identify the wood in the tree except for two of the nine logs used. The identification was made on geographic distribution and bark characters. Only two species of pine are native in Arkansas (Turner, '35). They were separated by the color and character of the bark and the presence of "small resin pits 1/16 inch in diameter" (Turner, '37) on the bark of *P. echinata* but not on *P. Taeda.*

B. Source and Selection.—The logs were selected in the storage yard of a sawmill at Sheridan, Arkansas. The source of the wood was within a twenty-five mile radius of this town, which is near the center of the north and south range of shortleaf pine and near the northern limits of the occurrence of loblolly pine, in this part of the southern pine belt.

Departure was taken from the rule of the American Society for Testing Materials ('33), which calls for taking consecutive specimens along cardinal radii of the log section without regard to structure. Selection was made for uniformity of growth, a representative range of ring structure, and for logs of large diameter. After a survey of the available logs the writer marked off a diameter on the selected ones. These were taken into the mill and a 2.5-inch plank was cut through each log at the marked diameter. Table I gives a brief description of the logs, and pl. 2 shows the structure of the planks. After the planks were dipped in "Dowicide" (an aqueous fungicide), they were bound face-to-face in two packages and shipped immediately to St. Louis.

C. Care and Preparation of the Specimens.—Two days after sawing, the planks were placed in a moist cold-storage room

TABLE I
DESCRIPTION OF LOGS

Log No.	Species	Number of growth rings	Diameter (inches)
1	Loblolly *(Pinus Taeda)*	85	20
2	Loblolly *(Pinus Taeda)*	60	22 Butt log
3	Loblolly *(Pinus Taeda)*	30	16
4	Shortleaf *(Pinus echinata)*	75	16 Butt log
5	Shortleaf *(Pinus echinata)*	200	28 Virgin growth
6	Shortleaf *(Pinus echinata)*	160	34 Virgin growth
7	Shortleaf *(Pinus echinata)*	100	19 Butt log
8	Shortleaf *(Pinus echinata)*	55	14
9	Shortleaf *(Pinus echinata)*	80	16 Butt log

where the temperature varied between 32 and 38° F. The planks were immediately cut into two equal lengths, and one half of each was removed to the laboratory, cut into sticks approximately 2.25 inches wide, and stacked for drying. The air-dry sticks were not cut into specimens until they had reached constant weight. The green halves of the planks were removed from cold storage, a plank at a time, and each was prepared and tested within three days.

In marking the planks for cutting into 2.25-inch sticks an attempt was made to include only uniform growth within each cross-section, and the cuts were made, as far as practical, parallel to the growth rings longitudinally The longitudinal rows of specimens included approximately the same growth rings in both the green and dry sections of the planks. The rough-sawn sticks were dressed by hand to uniform cross-sections approximately 2″ by 2 ″, with an open rotary planer (jointer). In this operation an attempt was made to true the sticks with the grain on all faces. The compression specimens were merely 6-inch sections cut from the dressed sticks. The tension specimens (fig. 3) were cut to shape on a band-saw, and then the small center test sections were dressed with a straight blade cutter head attached to a drill press as a shaper (pl. 1, fig. 1).

D. Designations of Specimens.—Each specimen is identified by a trinomial designation; for example, 4-A-7. The first num-

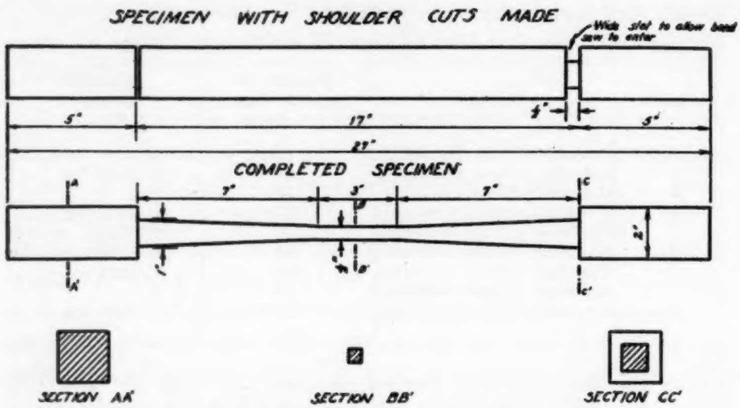

Fig. 3. Design of tension specimen used in this study.

ber refers to the log and the last number refers to the stick or the longitudinal row of specimens (pl. 2). The letter between the numbers designates the section of the original plank, cut in alphabetical order from the large end of the log. Each section was about 40 inches long, and the specimens were cut from it according to the suitability of the grain. Only specimens with identical designations may be regarded as matched, although those in the same longitudinal row may have been influenced by the same general growth conditions. The influence of "butt swell" upon the wood may be present in the "A" and "B" sections of Logs 2, 4, 7 and 9, so that these sections may not be comparable to other sections in the same row. There were bending tests and longitudinal shear tests made from this raw material in addition to the tension and compression tests reported here.

TESTS AND MEASUREMENTS

Wood is most often stressed in bending, in compression parallel to the grain, or in compression perpendicular to the grain, and there are adequate test data available in these strength categories. Though wood is strongest in tension parallel to the grain, its use in this manner is limited by its strength in shear along the grain, and since this is of very low order com-

paratively little attention has been given by engineers to the longitudinal tension test. The recent introduction of "timber connectors," devices for increasing the area of shear at the ends of tension members, should stimulate more work on tensile strength in the future, especially in connection with elastic properties and in consideration of abnormal types of wood.

For the present study the bending test has not been used because the applied force is resolved into longitudinal compression stresses, tension stresses, and shear stresses, which are unevenly distributed and undefinable for any certain area chosen for microscopic examination. The test for shear parallel with the grain would probably make a fruitful subject for the study of variability in wood, if it were not for the fact that no test has been devised in which longitudinal shear is known to be exclusively active.

The tension test and the compression test parallel to the grain are most easily understood, and the type of internal stress working on the individual fiber may be inferred. The fibers here are put to their best advantage, affording the best possible comparison. The stress in these tests is based on the transverse section of the wood which most truly represents the volumetric characteristics, i.e., descriptions and control data taken from the end section apply to the region of actual failure.

A. Tension Tests.—For the same reason that wood is rarely used as tension members in structural work, the testing of small clear specimens in tension is difficult. Since wood is about twenty times as strong in longitudinal tension as it is in longitudinal shear, the specimens must be designed to create enough longitudinal shear area to bear the load that will break the small section in the middle of the length (fig. 3, BB′). Further, there must be provided a gradual reduction in section area from the shoulder (CC′) to the test section to reduce the possibility of a concentration of internal stresses that will cause failure outside of the test section. Kollmann ('36) has illustrated a wide variety of tension-specimen designs proposed by different workers and used in different countries. The type of

specimen used in this study is identical with the standard in American practice except that the test section is reduced from six inches to three inches in length, and from $(5/8)^2$ inch to $(1/2)^2$ inch in sectional area. This specimen has been found to have the advantage of being less subject to damaging stresses in handling and less likely to fail in shear due to slight spiral or cross grain. In spite of the care taken in preparation, some of the specimens failed entirely in one of the tapered shanks, or failed in tension partially in the test section and partially in the shank with longitudinal shear connecting these fractures. When fracture did not occur entirely within the test section it may be assumed that the maximum stress given is conservative, i.e., the section had not yet sustained its breaking load when failure occurred elsewhere and ended the test. The elastic data, however, can always be taken as valid, since the strain measurements were confined to a two-inch portion of the measured section and were not affected by stresses and strains in other parts of the specimens.

The area of the test section was computed from micrometer measurements to 0.001 inch. Testing was conducted on an Amsler hydraulic testing machine (pl. 1, fig. 2). The load was applied to the shoulders of the specimens (fig. 3, CC′) through split steel rings with one-inch-square center openings which fitted about the shanks. These in turn rested upon spherically seated rings which transferred the load to the head blocks of the machine. Load was applied at an average speed of 0.007 inch per minute. Strain was measured with a "Last Word" extensometer reading to 0.0001 inch. This device measured extension over the middle two inches of the three-inch test section.

B. Compression Test.—The specimens for this test deviated from American standard practice in being six inches in length instead of eight inches, although they conformed to the 2″ × 2″ cross-section required. The ends of the specimens were sanded smooth and square, and length was measured to 0.01 inch with a steel scale; section dimensions were measured by micrometer to 0.001 inch. These tests were made on a Riehle three-screw

testing machine of 150,000 pounds capacity, equipped with a spherically seated head block. The testing speed was 0.024 inch per minute. Strain was taken as the distance moved by the head block and was measured with an Ames dial reading to 0.0005 inch. This method deviates from the recommendations of the American Society for Testing Materials which require strain to be measured between points six inches apart in the middle of an eight-inch specimen. The unit deformation over the full length has been reported to be consistently larger than that derived from the recommended method, and, further, the modulus of elasticity based on full-length deformation is better related to maximum strength (Brust and Berkley, '35).

C. Specific Gravity Determinations.—Specimens for specific gravity applying to the compression specimens were cut from the sticks near them. In the case of the tension tests, specific-gravity specimens were cut from unbroken portions of the 0.5-inch-square test sections of the tension specimens. If the test section had been shattered, a block was cut from identical growth rings traced into the shank.

The data for the determinations were obtained by weighing the blocks in air and in water, with a correction made for the water absorbed during the immersed weighing. Immersed weighing was done with a balance on which a weighted calibrated wire frame was substituted for one of the hanging pans. Specific-gravity values were referred to volumes as tested except for the air-dry tension test. It was found impossible to weigh accurately the dry two-gram blocks in water because of the air bubbles collecting on the wood due to displaced air. Specific-gravity determinations of both green and dry tension specimens were based upon their volumes in a resoaked condition. All specific gravities were corrected for benzol-soluble extractives; this tends to equate heartwood and sapwood.

D. Per Cent Summerwood.—Although the percentage of summerwood is not used as a correlation factor, a visual estimation is recorded for the compression test specimens, and a

value for each of the tension pieces was obtained by planimetering. This latter value represents the percentage of summerwood in the entire cross-section and may differ considerably from the proportion in the average growth ring, especially in wide-ringed material.

E. Moisture Content.—For green specimens the moisture content was derived from the specific-gravity specimen in the stick section of the same designation. This constituted merely a check against the possibility of the tested wood having dried below the fiber-saturation point which Berkley ('34) found to be 22.5 per cent for southern pine. One-inch sections were cut from the air-dry specimens and weighed immediately after each strength test. For the tension specimens this sample was taken from the large end of one of the tapered shanks.

F. Longitudinal Shrinkage.—Since this is the only physical property on the basis of which "compression wood" may be quantitatively segregated from normal wood, a series of these measurements was made in this study. For this purpose a four-inch section was taken at the mid-point of the original plank for each longitudinal row of specimens. This sample may be assumed to be fairly representative of the "B" and "C" specimens, but it is likely to indicate less shrinkage than is actually present in the "A" specimens and more than the "D" and "E" specimens. Especially is this so for the butt logs 2, 4, 7, and 9. This follows the findings of Pillow and Luxford ('37) that "compression wood" is much more frequent in the lower seventeen feet of shortleaf pine trees from Arkansas than at greater heights.

A 1″ × 1″ × 4″-piece was cut square with the growth rings from the 2″ × 2″ × 4″-sample, the ends sanded, and the center points marked. The difference in length from green to oven-dry was obtained by means of dial gauge reading to 0.0005 inch.

The physical data are given in columns 2 to 10 in tables II to V. The specimens represented here are those remaining after careful inspection had eliminated those with irregularities in gross character that might influence the data on ultimate

strength or stiffness. The strength figures given represent two aspects of the resistance to stress: (1) the maximum load that the material is able to bear, and (2) the resistance to deformation or the stiffness of the material. The modulus of elasticity represents the load required to lengthen or shorten a specimen, per unit length of the loading axis *during the time the material remains elastic.* This then is a measure of the stiffness of the material within the range where releasing the load will return it to its original form (length). Stiffness is included in the general term "strength"; however, in the indexes given in this paper "strength" indicates maximum or ultimate strength, and "stiffness" refers to the property evaluated by modulus of elasticity.

The strength-density index and the stiffness-density index of the wood refer strength and stiffness to factors other than specific gravity. If these indexes were multiplied by the specific gravity of wood substance they would give the stresses for the wood substance according to the argument presented above under "Density."

IV. Analysis

THE EFFECT OF GROWTH RING WIDTH

It may not be assumed from fig. 2 that growth rate in itself has an influence on the strength-density index, since no data are given on the variability within any growth-rate range. It is indicated that low strength is more likely to occur at more rapid growth rates regardless of specific gravity. The low average strength in wide-ring classes might be due merely to the more frequent occurrence of abnormal wood in them with random choice of specimen.

Figs. 4 to 9 present the distribution of strength- and stiffness-density indexes according to growth rate for the material tested. Considering the distribution of the individual specimens it is obvious that the correlation between axial strength properties and growth rate is poor. Large variations occur well within the growth-rate range acceptable for structural purposes, and many wide-ringed specimens show excellent

TABLE II

AXIAL TENSION TESTS, GREEN

(1) Specimen	(2) Specific gravity based on green volume*	(3) Moisture content in per cent of oven-dry weight	(4) Growth rings per inch	(5) Summerwood in per cent of cross-section area of specimen	(6) Longitudinal shrinkage in per cent of green length†	(7) Ultimate tensile strength	(8) Strength-density index, col. (7) / col. (2)	(9) Modulus of elasticity	(10) Stiffness-density index, col. (9) / col. (2)	(11) Average angle of fibrillar orientation in summerwood	
	(gr./cc.)	(%)		(%)	(%)	(lbs./in.²)	(lbs./in.²) / (gr./cc.)	(1000 lbs./in.²)	(1000 lbs./in.²) / (gr./cc.)	(degrees)	(sine)
1-B-1	.456	118	6.1	38	.051	*12,180***	26,750	1,530	3,360	8.2	.143
2-C-2	.531	109	4.0	50	.025	*13,000*	24,500	2,260	4,260	7.0	.122
2-C-3	.539	110	6.4	55	.082	*16,000*	29,700	1,870	3,470	6.5	.113
2-C-7	.491	114	5.4	54	.416	11,300	23,000	1,520	3,100	14.0	.242
3-A-1	.480	134	3.7	33	.251	8,750	18,220	1,175	2,450	15.2	.262
3-B-6	.396	117	6.3	22	.100	10,700	27,000	1,270	3,210	11.1	.193
4-D-2	.418	36	10.2	27	.088	*14,150*	33,900	1,830	4,380	8.6	.150
4-C-3	.440	25	6.9	34	.244	6,830	15,500	935	2,120	19.6	.335
4-C-4	.528	105	4.9	62	.266	10,100	19,100	1,060	2,050	19.6	.335
4-C-5	.456	126	9.2	46	.013	8,650	19,000	911	2,000	20.8	.355
6-B-2	.501	101	7.6	47	.051	14,250	28,450	2,940	5,870	8.0	.139
7-A-2	.549	85	12.0	38	‡– .050	17,000	31,000	1,990	3,625	13.6	.235
7-A-4	.600	78	6.5	52	.138	10,140	16,900	1,160	1,934	23.0	.391
7-A-6	.566	78	15.4	51	.013	*18,650*	33,000	2,890	5,110	11.5	.199
8-C-1	.448	129	6.8	35	.089	14,400	32,200	1,440	3,220	14.7	.254
8-C-2	.531	118	7.0	44	.063	*18,650*	35,150	1,955	3,680	10.5	.182
8-C-4	.568	114	6.7	51	.025	*18,500*	32,600	2,650	4,670	9.2	.160
9-A-1	.493	117	3.3	48	– .038	11,250	22,800	1,470	2,980	14.3	.247
9-C-1	.501	120	4.6	46	.089	17,300	34,600	2,035	4,060	7.0	.122
9-A-2	.550	105	3.2	58	– .037	*10,180*	18,500	1,155	2,100	19.0	.326
9-C-2	.503	122	5.9	39	.088	*15,860*	31,600	2,200	4,370	8.0	.139
9-A-3	.491	91	8.8	69	.728	7,140	14,540	719	1,462	32.2	.533
9-C-3	.485	116	5.6	45	.278	*15,900*	32,800	1,990	4,110	14.9	.257
9-A-4	.540	106	4.0	81	1.340	7,500	13,900	667	1,236	30.5	.508
9-C-4	.427	123	4.3	35	.478	8,990	21,000	1,070	2,505	24.1	.408

* Specific gravity is corrected for benzol extractive.
† The specimens were taken between the "B" and "C" strength specimens.
‡ (–) signifies an extension in drying.
** Italics indicate fracture occurred outside the measured section of the specimen; this value may be low.

TABLE III
AXIAL TENSION TESTS, AIR-DRY

(1) Specimen	(2) Specific gravity based on green volume*	(3) Moisture content in per cent of oven-dry weight	(4) Growth rings per inch	(5) Summerwood in per cent of cross-section area of specimen	(6) Longitudinal shrinkage in per cent of green length†	(7) Ultimate tensile strength	(8) Strength-density index, col. (7) / col. (2)	(9) Modulus of elasticity	(10) Stiffness-density index, col. (9) / col. (2)	(11) Average angle of fibrillar orientation in summerwood	
	(gr./cc.)	(%)		(%)	(%)	(lbs./in.^{2})	(lbs./in.^{2}) / (gr./cc.)	(1000 lbs./in.^{2})	(1000 lbs./in.^{2}) / (gr./cc.)	(degrees)	(sine)
1-D-1	.407	10.0	10.1	–	.051	*15,950***	39,200	2,300	5,650	7.7	.134
1-C-3	.511	10.4	7.2	55	1.500	13,000	25,400	1,428	2,650	19.6	.335
1-C-4	.501	10.4	4.6	67	.754	12,900	25,750	1,230	2,455	22.9	.389
1-C-5	.523	10.1	4.6	61	.839	10,560	20,200	1,206	2,306	26.4	.445
2-B-2	.534	10.1	3.2	35	.025	13,930	26,000	2,170	4,060	13.4	.232
2-A-3	.524	10.9	4.4	70	.062	18,400	35,100	1,640	3,130	20.3	.347
2-A-6	.506	10.6	3.3	84	.151	10,800	21,350	1,590	3,120	33.2	.548
2-B-7	.480	10.4	5.4	31	.200	12,250	25,500	1,610	3,355	17.6	.302
3-C-1	.426	9.6	3.4	37	.251	19,850	46,600	2,500	5,870	13.8	.238
3-C-2	.519	9.8	3.0	69	.062	17,400	33,500	1,875	3,610	19.9	.340
3-D-6	.432	9.8	4.8	71	.020	13,700	31,700	1,640	3,800	18.0	.309
4-A-1	.502	10.9	12.0	36	.076	*22,500*	44,800	2,920	5,810	8.0	.139
4-A-3	.497	10.3	5.6	30	.244	*14,500*	29,200	1,895	3,810	14.8	.255
4-A-5	.451	9.9	7.4	29	.013	14,800	32,800	1,510	3,350	17.7	.304
5-D-3	.495	10.3	18.4	31	.063	14,600	29,500	2,790	5,640	4.8	.084
5-D-4	.497	10.4	18.0	34	.005	13,700	27,600	2,140	4,300	6.2	.108
6-A-2	.491	9.0	7.3	45	.051	*16,100*	32,800	2,660	5,420	12.8	.222
7-B-2	.538	10.8	10.1	48	‡– .051	*13,100*	24,350	1,770	3,290	17.9	.308
7-B-4	.416	10.2	9.4	27	.138	13,700	32,900	1,540	3,700	17.2	.296
7-B-6	.546	10.4	12.1	47	.013	18,400	33,700	2,440	4,460	11.4	.198
8-A-1	.506	9.2	7.2	46	.069	16,970	33,500	1,730	3,420	20.5	.350
8-A-2	.560	9.6	7.8	56	.063	*16,800*	30,000	2,130	3,800	17.6	.302
8-B-3	.592	9.7	7.3	60	.057	22,100	37,300	2,440	4,120	17.4	.299
8-A-4	.482	8.7	6.7	36	.025	*13,200*	27,400	1,665	3,460	19.0	.326
9-E-1	.455	8.8	4.0	–	.089	*14,400*	31,650	2,460	5,410	8.6	.150
9-D-4	.451	8.9	4.2	49	.476	11,300	25,050	1,327	2,940	23.2	.394

* Specific gravity was corrected by deducting benzol extractive.
† The specimens were taken between the "B" and "C" strength specimens.
‡ (–) signifies an extension in drying.
** Italics indicate fracture occurred outside the measured section of the specimen; this value may be low.

TABLE IV

AXIAL COMPRESSION TESTS, GREEN

(1) Specimen	(2) Specific gravity based on green volume*	(3) Moisture content in per cent of oven-dry weight	(4) Growth rings per inch	(5) Estimated width of summerwood in per cent of growth ring width	(6) Longitudinal shrinkage in per cent of green length†	(7) Maximum crushing strength	(8) Strength-density index, col. (7) / col. (2)	(9) Modulus of elasticity	(10) Stiffness-density index, col. (9) / col. (2)	(11) Average angle of fibrillar orientation in summerwood	
	(gr./cc.)	(%)		(%)	(%)	(lbs./in.^{2})	(lbs./in.^{2}) / (gr./cc.)	(1000 lbs./in.^{2})	(1000 lbs./in.^{2}) / (gr./cc.)	(degrees)	(sine)
1-B-1	.444	118	7.0	25	.051	3,360	7,570	776	1,748	8.4	.146
1-A-2	.575	35	6.0	75	1.640	4,190	7,290	505	879	–	–
1-B-4	.569	60	3.7	60	.754	3,780	6,640	604	1,060	28.8	.482
1-B-5	.506	68	5.0	55	.839	3,440	6,800	615	1,215	–	–
2-D-1	.458	124	3.9	30	.025	3,420	7,470	729	1,590	10.2	.177
2-D-2	.487	109	4.4	35	.025	3,810	7,820	790	1,620	10.8	.187
2-D-3	.478	110	5.9	30	.062	3,750	7,850	912	1,910	6.0	.105
3-A-1	.434	134	4.1	45	.251	3,380	7,790	775	1,784	12.4	.215
4-C-1	.433	120	12.6	25	.076	3,770	8,710	925	2,135	7.2	.125
4-D-2	.538	36	8.9	25	.088	3,750	6,970	750	1,393	7.0	.122
5-B-1	.544	85	18.6	50	.013	3,910	7,190	789	1,450	8.6	.150
5-B-2	.566	65	17.5	45	.078	4,380	7,740	904	1,598	8.7	.151
5-B-3	.535	29	22.2	40	.083	5,220	9,760	902	1,687	7.0	.122
5-B-4	.521	31	17.5	35	.005	4,450	8,540	1,100	2,109	6.8	.118
6-B-2	.476	101	8.3	50	.051	3,380	7,110	878	1,847	8.0	.139
6-B-6	.453	30	4.7	50	.040	3,140	6,930	610	1,347	21.3	.363
6-B-7	.445	26	5.0	40	.086	3,170	7,120	654	1,469	19.8	.339
7-A-2	.545	85	11.9	50	‡– .050	4,000	7,340	1,020	1,871	10.6	.184
7-A-3	.543	56	11.4	45	– .089	3,330	6,130	546	1,006	20.0	.342

TABLE IV (Continued)

(1) Specimen	(2) Specific gravity based on green volume*	(3) Moisture content in per cent of oven-dry weight	(4) Growth rings per inch	(5) Estimated width of summerwood in per cent of growth ring width	(6) Longitudinal shrinkage in per cent of green length†	(7) Maximum crushing strength	(8) Strength-density index, col. (7) / col. (2)	(9) Modulus of elasticity	(10) Stiffness-density index, col. (9) / col. (2)	(11) Average angle of fibrillar orientation in summerwood	
	(gr./cc.)	(%)		(%)	(%)	(lbs./in.^{2})	(lbs./in.^{2}) / (gr./cc.)	(1000 lbs./in.^{2})	(1000 lbs./in.^{2}) / (gr./cc.)	(degrees)	(sine)
7-A-4	.592	78	6.0	50	.138	3,840	6,480	639	1,080	27.0	.454
7-A-5	.588	80	10.5	60	– .037	4,550	7,740	894	1,520	12.0	.208
7-A-6	.557	78	12.7	45	.013	4,260	7,640	828	1,484	11.2	.194
8-C-1	.469	129	8.6	40	.089	4,230	9,020	945	2,015	11.4	.198
8-C-3	.511	104	7.3	40	.057	4,590	8,990	937	1,633	12.2	.211
8-C-4	.499	114	7.6	40	.025	4,850	9,720	964	1,930	12.1	.210
9-A-1	.471	117	4.6	35	– .038	3,460	7,350	684	1,452	10.2	.177
9-C-1	.462	120	4.4	35	.089	3,600	7,790	772	1,670	8.0	.139
9-A-3	.513	91	3.8	50	.728	3,250	6,340	491	957	26.6	.448
9-A-4	.477	106	4.1	45	1.340	3,320	6,960	501	1,050	29.2	.488

* Specific gravity is corrected for benzol extractive.
† The shrinkage specimens were taken between the "B" and "C" strength specimens.
‡ (–) signifies an extension in drying.

TABLE V

AXIAL COMPRESSION TESTS, AIR-DRY

(1) Specimen	(2) Specific gravity based on air-dry volume*	(3) Moisture content in per cent of oven-dry weight	(4) Growth rings per inch	(5) Estimated width of summerwood in per cent of growth ring width	(6) Longitudinal shrinkage in per cent of green length†	(7) Maximum crushing strength	(8) Strength-density index, col. (7) / col. (2)	(9) Modulus of elasticity	(10) Stiffness-density index, col. (9) / col. (2)	(11) Average angle of fibrillar orientation in summerwood	
	(gr./cc.)	(%)		(%)	(%)	(lbs./in.²)	(lbs./in.²) / (gr./cc.)	(1000 lbs./in.²)	(1000 lbs./in.²) / (gr./cc.)	(degrees)	(sine)
1-D-1	.522	7.3	11.0	30	.051	8,260	15,800	1,440	2,760	6.2	.108
1-D-2	.570	8.3	7.1	20	1.640	7,650	13,420	1,052	1,848	27.9	.468
1-C-4	.558	7.4	4.6	60	.754	7,720	13,840	1,050	1,880	27.6	.463
1-C-5	.568	6.8	5.3	60	.839	7,500	13,200	1,010	1,780	29.8	.497
2-B-1	.580	7.3	5.4	35	.025	9,150	15,780	1,520	2,620	9.5	.165
2-B-2	.618	7.8	4.3	35	.025	9,630	15,580	1,568	2,540	8.0	.139
2-A-3	.616	8.8	5.4	35	.062	9,110	14,800	1,505	2,445	12.8	.222
2-A-6	.561	7.7	4.2	35	.151	7,490	13,330	1,000	1,785	25.2	.426
2-B-7	.586	7.8	5.2	40	.200	8,120	13,850	1,150	1,962	21.1	.360
2-A-8	.560	7.9	4.7	35	.123	8,470	15,120	1,467	2,620	14.1	.244
3-C-1	.502	8.7	4.7	30	.251	7,970	15,870	1,574	3,140	6.9	.120
3-C-2	.482	8.6	3.5	35	.062	8,020	16,620	1,450	3,005	12.0	.208
3-C-4	.451	8.6	4.0	20	.018	7,220	16,000	1,380	3,060	11.8	.205
3-D-5	.512	9.0	3.2	30	.020	6,970	13,600	1,250	2,440	14.3	.247
3-D-6	.488	8.4	4.7	20	.100	7,260	14,900	1,305	2,675	13.6	.235
4-A-1	.526	7.7	10.9	35	.076	9,500	18,050	1,770	3,360	8.7	.151
4-B-2	.489	8.4	8.6	35	.088	9,350	19,100	1,780	3,640	9.0	.156
4-A-4	.566	8.5	5.2	35	.266	9,070	16,000	1,380	2,440	16.0	.276
5-D-1	.565	8.6	24.4	40	.013	8,900	15,750	1,671	2,960	7.2	.125
5-D-2	.667	8.9	20.9	35	.076	10,530	15,800	1,980	2,970	5.4	.094

TABLE V (Continued)

(1) Specimen	(2) Specific gravity based on air-dry volume*	(3) Moisture content in per cent of oven-dry weight	(4) Growth rings per inch	(5) Estimated width of summerwood in per cent of growth ring width	(6) Longitudinal shrinkage in per cent of green length†	(7) Maximum crushing strength	(8) Strength-density index, col. (7) / col. (2)	(9) Modulus of elasticity	(10) Stiffness-density index, col. (9) / col. (2)	(11) Average angle of fibrillar orientation in summerwood	
	(gr./cc.)	(%)		(%)	(%)	$(lbs./in.^2)$	$(lbs./in.^2)/(gr./cc.)$	$(1000\ lbs./in.^2)$	$(1000\ lbs./in.^2)/(gr./cc.)$	(degrees)	(sine)
5-D-3	.585	9.2	21.2	30	.063	10,100	17,260	1,775	3,040	5.0	.087
5-C-5	.562	9.3	16.2	35	.013	8,330	14,800	1,500	2,665	13.4	.232
6-A-2	.548	8.9	9.4	45	.051	8,500	15,500	1,735	3,170	7.1	.124
6-A-3	.520	9.0	5.9	35	.089	7,990	15,350	1,610	3,100	7.2	.125
6-A-6	.523	8.7	5.5	35	.040	7,000	13,400	1,255	2,400	15.0	.259
6-A-7	.447	11.1	4.4	35	.086	7,040	15,720	1,184	2,650	19.0	.326
7-B-1	.584	9.3	14.8	35	.025	8,840	15,120	1,776	3,040	11.6	.201
7-B-2	.635	9.8	9.2	45	‡− .050	9,050	14,240	1,700	2,680	14.4	.249
7-B-3	.586	10.1	7.4	30	− .089	8,140	13,900	1,370	2,340	13.4	.232
7-B-4	.549	9.9	7.3	30	.138	7,300	13,300	1,160	2,110	17.5	.301
8-A-1	.572	8.1	7.9	45	.084	8,420	14,700	1,270	2,220	17.8	.306
8-A-2	.637	7.3	8.1	50	.063	8,620	13,520	1,420	2,230	19.3	.331
8-A-4	.616	7.8	7.3	45	.025	8,590	13,930	1,380	2,240	18.9	.324
9-E-1	.497	9.1	5.8	30	.089	7,740	15,560	1,700	3,420	4.6	.080
9-E-3	.509	9.2	8.6	40	.278	6,740	13,230	1,160	2,280	20.6	.352
9-D-4	.484	9.3	4.6	40	.478	6,400	13,200	985	2,033	24.0	.407

* Specific gravity is corrected for benzol extractive.
† The shrinkage specimens were taken between the "B" and "C" strength specimens.
‡ (−) signifies an extension in drying.

strength properties for their densities. Although a larger random representation would perhaps show that there is a concentration of "abnormal" material in the range of wide rings, it is not indicated that width of growth ring in itself is a considerable factor in the resistance of solid material of the wood to axial stresses.

Since data on tension strength are rather rare in the literature these charts are of interest in comparing the tension and compression stresses under different moisture conditions considering the data as groups of specimens from the same lot of wood. Any solution for the true mechanism of stress resistance must consider the facts shown here: that in the green condition axial tension strength of the wood substance is more than twice as great as axial compression strength; and that drying has less effect upon tension strength and stiffness than upon compression strength and stiffness.

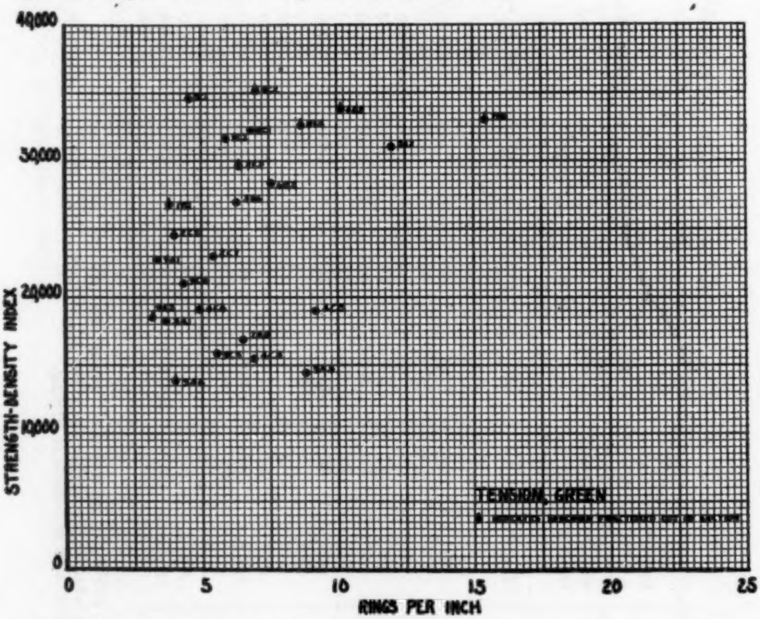

Fig. 4. Axial strength-density index (ultimate strength ÷ specific gravity) plotted over growth rate for green specimens.

The normality of the wood used in this study may be judged by comparison with the average data given by Markwardt and Wilson ('35) for *Pinus echinata,* taken near Malvern, Arkansas. The average maximum crushing strength in compression parallel to the grain in green condition was 3570 lbs. per sq. in.; the average specific gravity, at test, was 0.477, and the average number of rings per inch was 13.4. These data

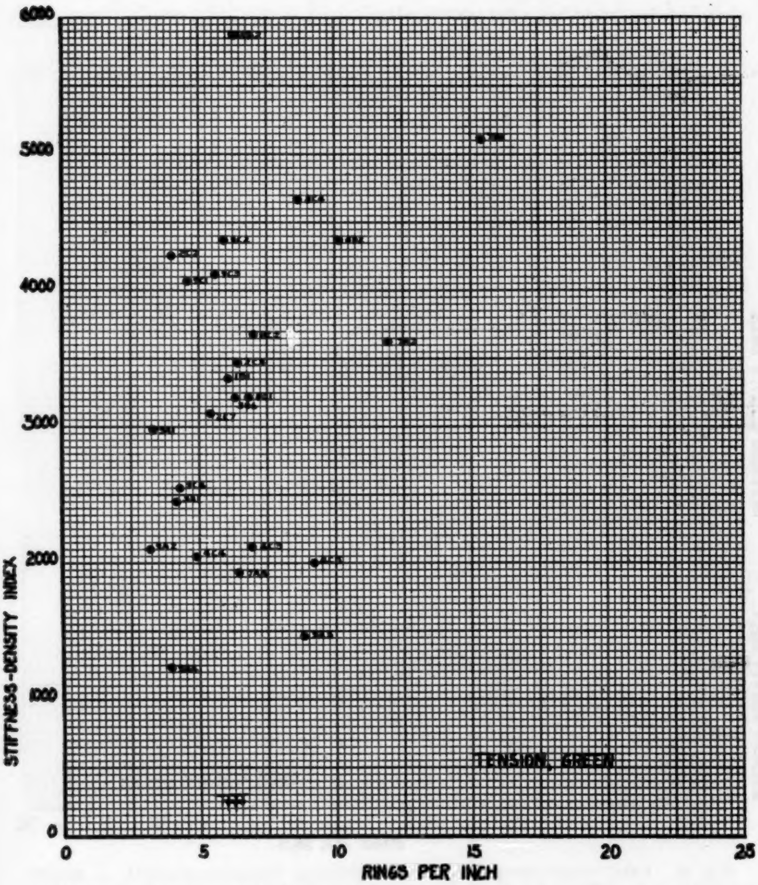

Fig. 5. Axial tension stiffness-density index (modulus of elasticity ÷ specific gravity) plotted over growth rate for green specimens.

are comparable to those of the compression tests used in this study and when calculated into an average strength-density index and plotted in fig. 6 are seen to fit quite well. The point is represented by the X mark at 13.4 rings per inch.

CORRELATION OF STRENGTH AND STIFFNESS WITH FIBRILLAR ORIENTATION

Since low strength for its density is known to be accompanied by high angle of fibrillar orientation in "compression

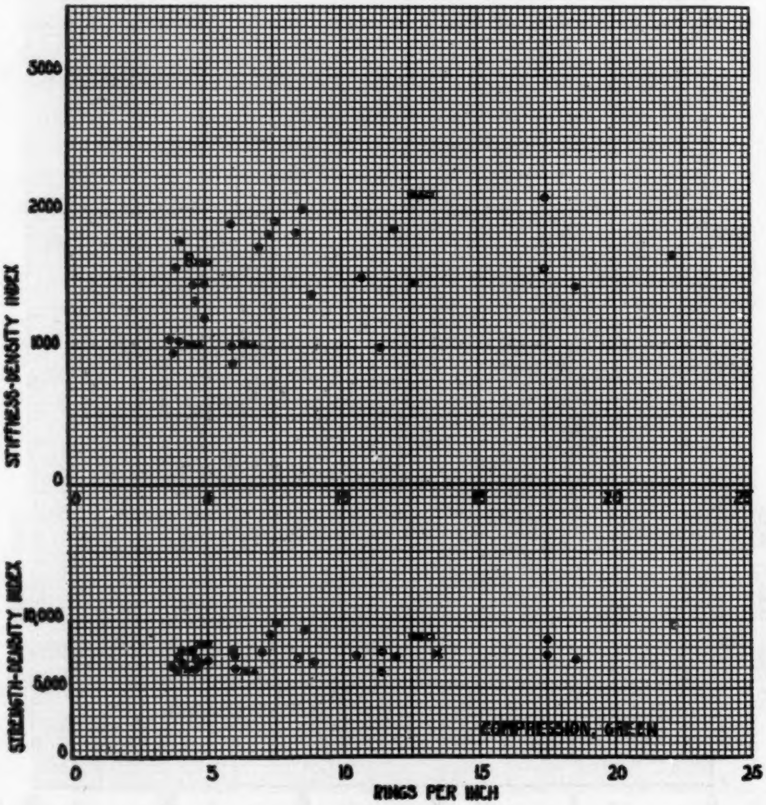

Fig. 6. Axial compression strength-density index (ultimate strength ÷ specific gravity) and stiffness-density index (modulus of elasticity ÷ specific gravity) plotted over growth rate for green specimens. X indicates strength-density index of average test for *Pinus echinata* from Arkansas (Markwardt and Wilson, '35).

wood,'' the present randomly selected groups of specimens were examined to show the effect on strength of this measurable feature of cell-wall structure. This relationship for compression strength, bending strength, and stiffness has been treated briefly by Pillow and Luxford ('37) and reviewed earlier in this paper.

Fairly simplified technique had to be developed to obtain representative averages for the comparatively large amount of material involved in this study. Sampling was done in the following manner. Blocks of material from the test specimens were cloven radially. Under the proper lighting angle there

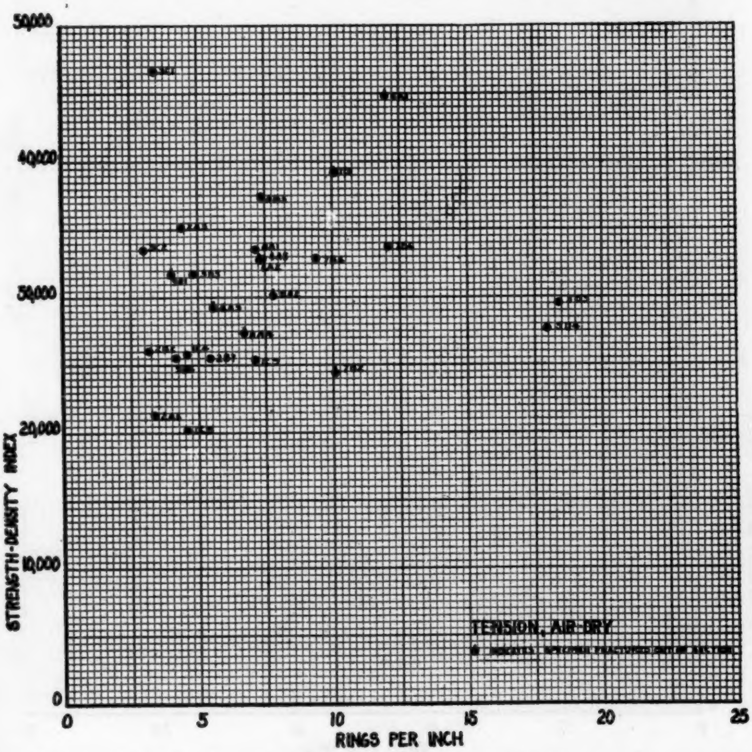

Fig. 7. Axial tension strength-density index (ultimate strength ÷ specific gravity) plotted over growth rate for air-dry specimens.

could be seen on the faces of the split halves small radial groups of fibers, often one cell thick, whose ends had been loosened from the wood. These one-celled rows were carefully cut free with a micro-knife and placed in benzol. When the benzol had displaced the air in the cells these "sections" were put in temporary microscope slide mounts in ordinary rubber cement. The non-swelling medium was designed to prevent

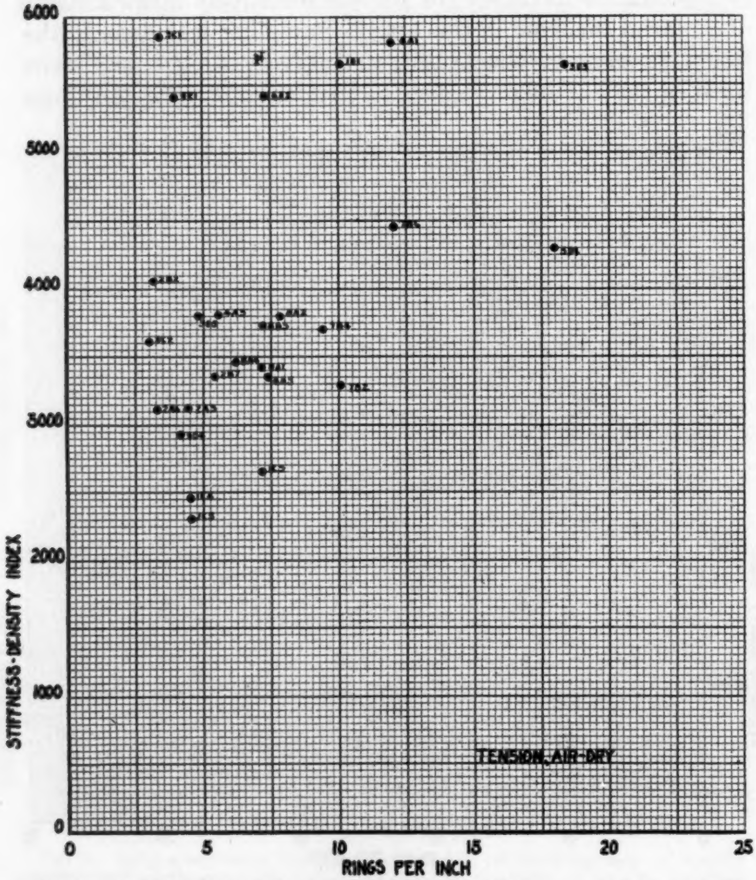

Fig. 8. Axial tension stiffness-density index (modulus of elasticity ÷ specific gravity) plotted over growth rate for air-dry specimens.

the disappearance of any fibrillar checks or striations occasioned by drying. The search for indication of slope of fibrils was made at 440 ×. Often the plane of orientation was indicated by cleavages in the central wall due to the splitting of

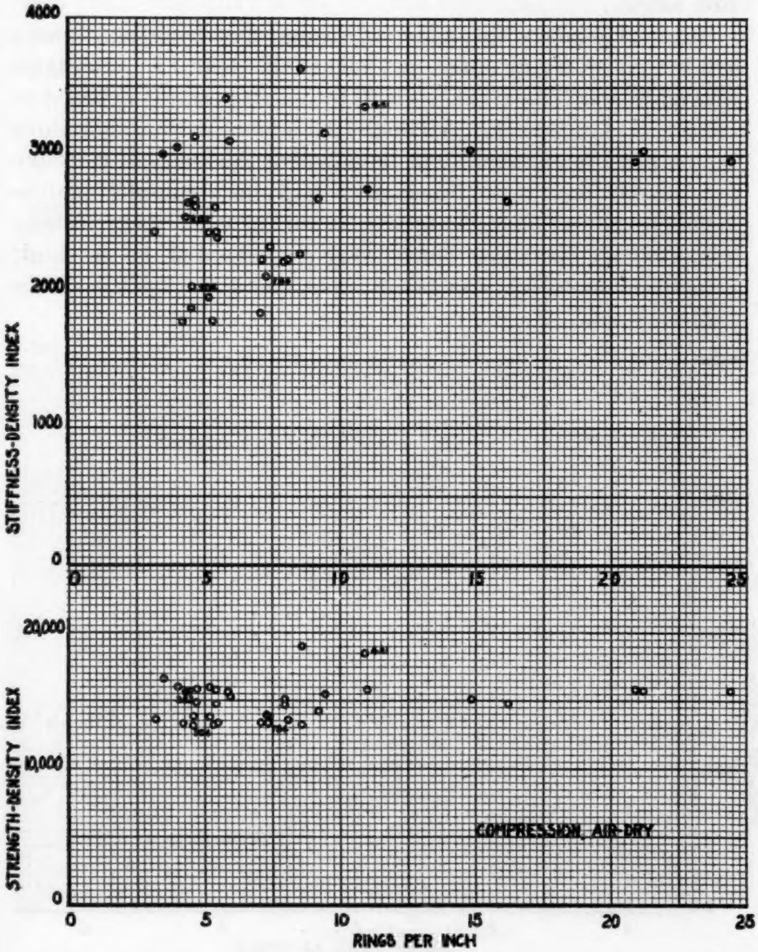

Fig. 9. Axial compression strength-density index (ultimate strength ÷ specific gravity) and stiffness-density index (modulus of elasticity ÷ specific gravity) plotted over growth rate for air-dry specimens.

the wood. Summerwood fibers of low angle were the most difficult, and often considerable searching for a single measurement was entailed. In difficult observations polarized light was employed to accentuate discontinuities and to check orientation angles.

Measurements were made by means of a cross-hair and a graduated revolving stage, and only in the clear, i.e., away from pits and rays. The average angle for each specimen is based on twenty measurements distributed as evenly as possible along the split radius according to the relative thickness of the summerwood. The tension specimens had more complete representation since they contained fewer growth rings. Many compression specimen rings were represented by a single measurement which was taken from about the middle of the summerwood.

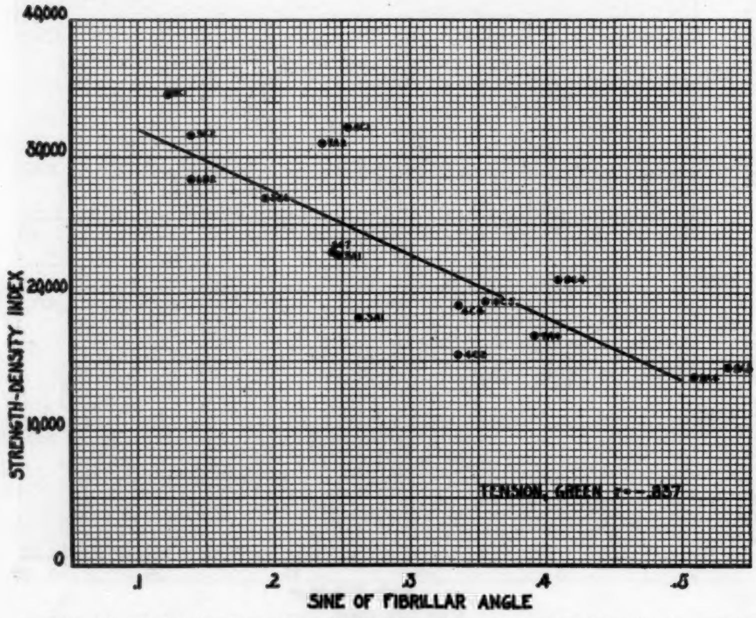

Fig. 10. Axial tension strength-density index (ultimate strength ÷ specific gravity) correlated with sine of average fibrillar angle in summerwood for green specimens.

For correlation purposes the fibrillar angle of summerwood only was measured. This deviates from the method of Pillow and Luxford ('37), who used an average angle "weighted on the basis of the proportions of springwood and summerwood and their respective slope." True representation of the wood for strength correlation requires weighting on the basis of

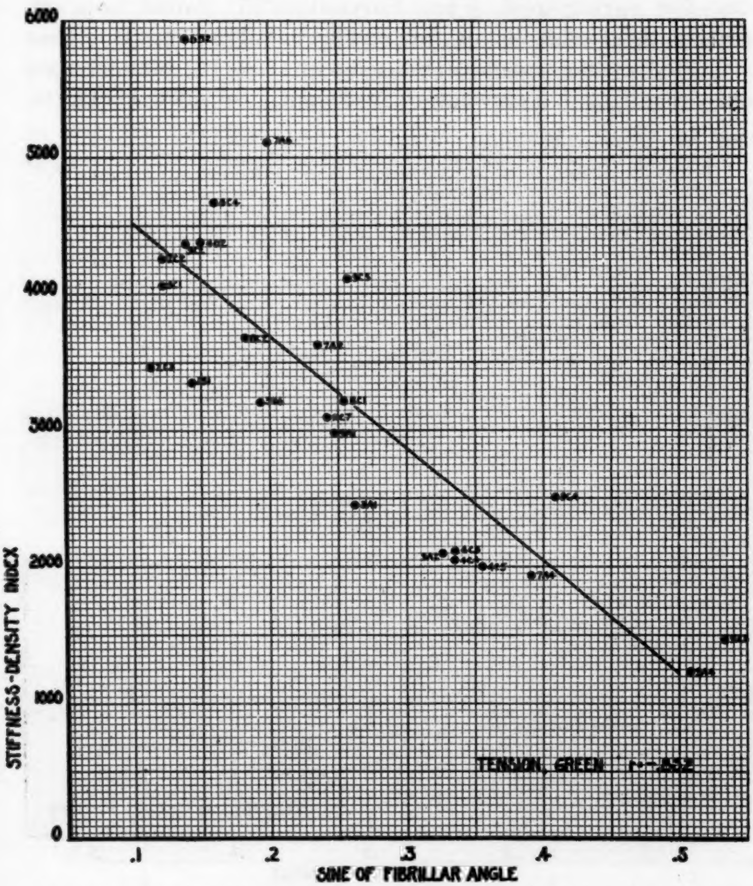

Fig. 11. Axial tension stiffness-density index (modulus of elasticity ÷ specific gravity) correlated with sine of average fibrillar angle in summerwood for green specimens.

weight. As a check on the validity of using only summerwood, twenty measurements each were made in the springwood of twelve tension specimens representing the complete range of angular variation. Averages of fibrillar angles were then calculated with weighting based on area proportion and specific gravity (constant weighting of three for summerwood and one for springwood, since Forsaith ('33) found approximately this relationship for southern yellow pine). These weighted averages were correlated with those for summerwood only, resulting in a correlation coefficient, r, of +.970, $t = 12.618$.

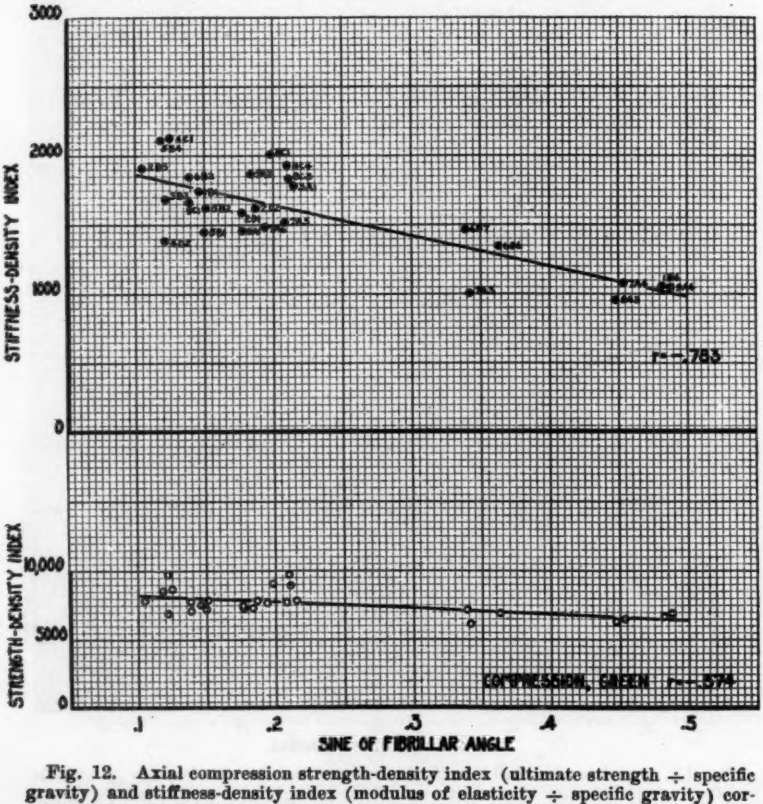

Fig. 12. Axial compression strength-density index (ultimate strength ÷ specific gravity) and stiffness-density index (modulus of elasticity ÷ specific gravity) correlated with sine of average fibrillar angle in summerwood for green specimens.

The average fibrillar angles of summerwood are given in column 11 of tables II to V, along with their sines. Graphical correlation of the sines with strength- and stiffness-density indexes for axial tension and axial compression in green and air-dry wood is shown in figs. 10 to 15. The product-moment regression line is superimposed on each chart. A summary of the product moment correlation coefficients and their reliabilities is given in table VI. All of the correlation coefficients are significant under the t test except that for dry tension strength-density, for which the probability of r being unrepresentative is slightly greater than 0.1. Unfortunately many of the

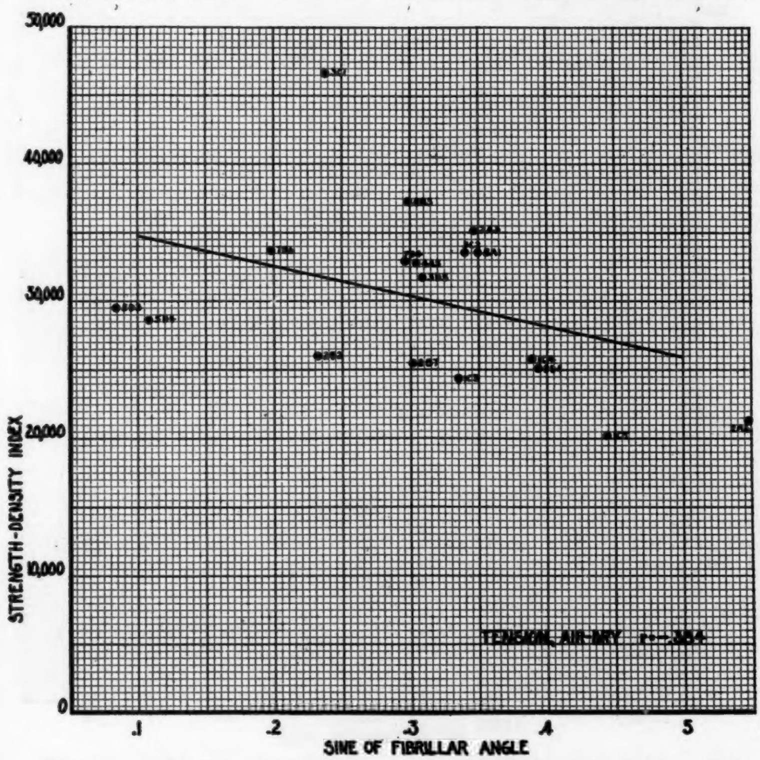

Fig. 13. Axial tension strength-density index (ultimate strength ÷ specific gravity) correlated with sine of average fibrillar angle in summerwood for air-dry specimens.

stronger specimens in this series failed to break in the test section and could not be used as reliable.

There appears to be little doubt but that the angle of fibrillar orientation or some factor closely associated with it is effective in determining the resistance of the wood to axial stresses. Whether the relationship in all series actually conforms to a

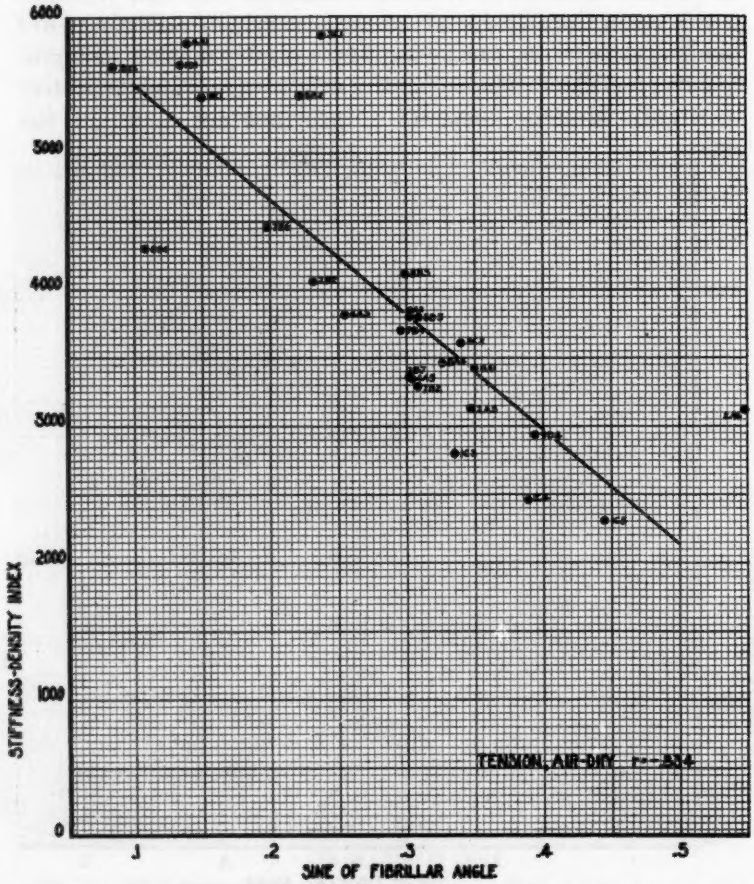

Fig. 14. Axial tension stiffness-density index (modulus of elasticity ÷ specific gravity) correlated with sine of average fibrillar angle in summerwood for air-dry specimens.

straight line may not be determined by the amount and distribution of the data at hand, though any curvilinearity in compression relationships would seem to be slight.

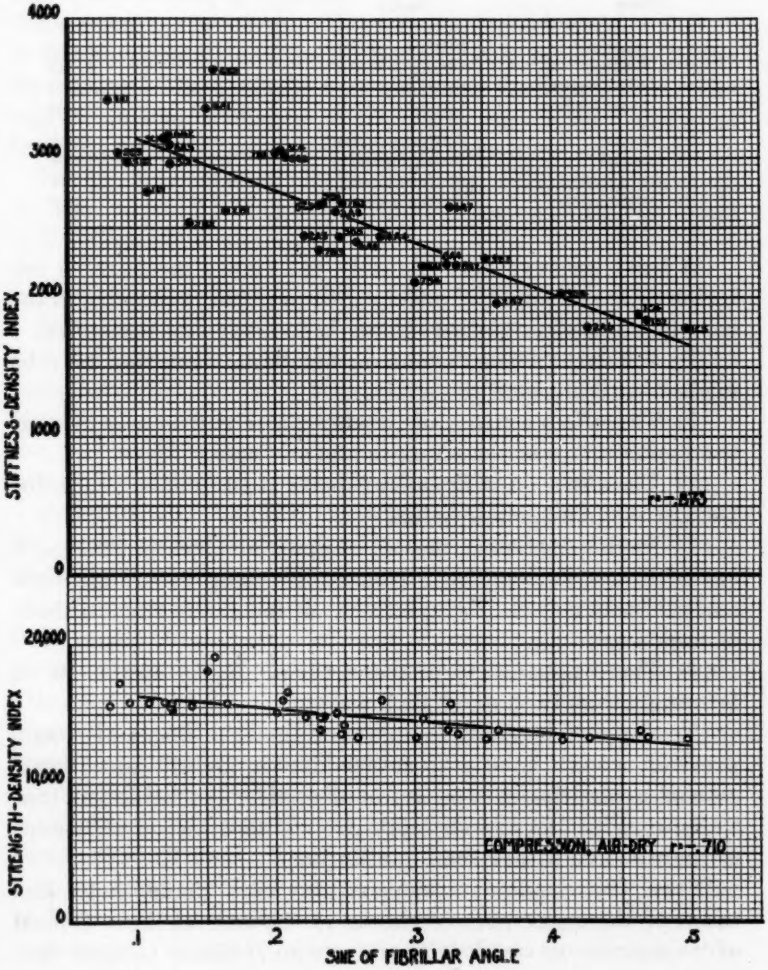

Fig. 15. Axial compression strength-density index (ultimate strength ÷ specific gravity) and stiffness-density index (modulus of elasticity ÷ specific gravity) correlated with sine of average fibrillar angle in summerwood for air-dry specimens.

TABLE VI

CORRELATION COEFFICIENTS OF RELATIONSHIPS OF STRENGTH- AND STIFFNESS-DENSITY INDEXES WITH AVERAGE ANGLE OF FIBRILLAR ORIENTATION IN SUMMERWOOD

Stress	Index	r	t
Green tension	Stiffness-density	–.832	7.192
Green tension	Strength-density	–.837	5.723
Green compression	Stiffness-density	–.783	6.294
Green compression	Strength-density	–.574	3.505
Dry tension	Stiffness-density	–.834	7.404
Dry tension	Strength-density	–.384	1.664
Dry compression	Stiffness-density	–.873	10.438
Dry compression	Strength-density	–.710	5.879

At least we have here the only yet known measurable criterion of the strength of wood substance, and its control in the investigation of any other factor is indicated as necessary.

The following observations on fibrillar orientation may be made from a study of the charts:

(1) The effect on tension strength and stiffness is greater than upon compression strength and stiffness.

(2) The effect on stiffness is greater than upon strength for both tension and compression.

(3) Drying increases the effect upon compression strength and stiffness, i.e., drying increases the compression strength and stiffness more in the specimens of low angle than in those of high angle.

(4) There appears to be more variability in specimens of low angle than in those of high angle.

(5) Support is given to the view that the fibers of "compression wood" have a structure that is merely an extreme case of a condition that occurs in all conifer tracheids and that "abnormality" in the strength properties of wood substance is quantitative rather than qualitative.

When the angular measurements were made, note was taken of the occurrence of checks in the central layer typical of "compression wood." There was no evidence to show that checks were associated with a constant limit in fibrillar angle, nor that their presence explained the variation of any of the strength properties at any given fibrillar angle. Checks were

noted with angles as low as 15° but many fibers with angles as high as 28° were found to be unchecked. Generally tension specimens exhibited checks at a slightly lower fibrillar angle than compression specimens.

Re-examination of growth rate as a factor showed that it is not responsible for the deviations still remaining in the correlation. The average ring width for specimens below the regression line is in none of the series significantly different from the average for specimens above the line.

The plotting in these charts serves as reference in a search for the remaining factors controlling the resistance of wood to longitudinal stress.

EXAMINATION OF TENSION FRACTURES OF THE WOOD

The fractured portions of the tension specimens were sawn out and carefully preserved for examination under a 42.5 × (supplemented by 130 ×) binocular microscope. Mounting the blocks on a universally movable holder enabled adjustment for the best possible light incidence on the fibers so that the relation of fiber fracture to wood fracture could be studied.

Generally brash failure for weak specimens and splintering for strong ones were noted. Green specimens splintered more than dry ones. Many strong dry specimens appeared to the eye to have brash failure but magnification showed the fracture to be composed of a large number of minute splinters of single fibers or small groups. Typical brash failure of weak wood exhibited the plane of fracture extending transversely across large groups of cells. Springwood portions were normally brash and summerwood splintered.

Cell end fracture appeared mostly transverse in summerwood fibers of strong pieces and frayed or spirally torn in those of weak ones. Springwood fiber end fracture was irregular, mostly with its general plane coinciding with the plane of failure of the wood.

Commonly fiber fracture was observed to coincide with edges of wood rays in summerwood, the cells being broken off in radial rows. This ray association was less regular in springwood. Very strong summerwood fibers fractured independ-

ently, and the point of fracture of very weak ones was determined by the general plane of fracture of the wood (brash fracture). Some summerwood fibers not fractured but with intact ends projecting were commonly found at the fracture of very strong dry specimens. In the green series a few of these fibers were usually found even in the weakest specimens.

Longitudinal cleavage of the wood (corollary to splintering) was most profuse in strong and green specimens. Gross tangential longitudinal cleavage was not confined to either type of tissue, and often the cleavage plane was observed to extend across the border between springwood and summerwood without interruption. Commonly the lateral fracture occurred through the cell in springwood and apparently between fibers in summerwood. Exceptions to this rule were observed in the occasional occurrence of torn summerwood lateral walls in weak dry specimens and the frequent untorn springwood lateral walls of strong green specimens. Where the walls appeared untorn in lateral separation, fragments of the outer layer of the secondary wall were frequently seen clinging to the cells. On flat planes there were areas where longitudinal plates of the outer layer (with middle lamella and primary walls between) had been pulled laterally from between the fibers on the opposite face of the plane. It was also frequently observed that the outer layer had been pulled from the central layer in transverse strips (according to the orientation of the cellulose in the outer layer). This separation of fibers at the interface between outer and central layer of the secondary wall was confirmed in the study of macerated fibers (pl. 3, figs. 1 and 3).

The implication from the more frequent occurrence of unfractured cells (central layer) in the green condition is that drying tightens the bond between outer and central layer, increasing the strain on the central layer and causing cell fracture rather than cell separation.

No constant criteria were derived from this study for the explanation of differences in strength between specimens of the same average angle of fibrillar orientation, though some

of the stronger specimens in the high-angle range exhibited the strong type of fracture (splinter) and some of the weaker specimens in the low-angle range tended to exhibit the weak type of fracture (brash). Weak green tension specimens 9-C-4 and 9-A-3 (figs. 4 and 5) did not have brash summerwood fractures and had some unfractured fibers projected at the wood fracture. Strong dry tension specimens 5-D-3 and 5-D-4 (figs. 7 and 8) were brash.

MICROSCOPIC EXAMINATION OF FIBERS

For studying the relation of failure to fiber structure a method of microscopic preparation was sought which would give most clearly the actual picture of conditions at the time of fracture. Isolation of fibers, under a dissecting microscope, with the aid of chemical maceration was chosen for this end. Short splinters were carefully split from fractured areas, boiled for several minutes (being held in water with a wire clamp), and treated with Jeffrey's macerating fluid (equal parts of 10 per cent chromic acid and 10 per cent nitric acid) until several radial layers of fibers were loose enough to be removed by means of chisel-pointed needles. These radial groups and some single fibers, after washing, were lifted on a needle from the water by surface tension and mounted on a microscope slide in glycerine jelly. No stain was used since it might have clouded the structural features that were deemed important in this study. A polarizing microscope was used to identify structural detail and to accentuate fracture planes.

Tension fiber fracture.—Springwood tracheids had fractured in no definable pattern (pl. 4, fig. 6), just as was noted in the low-power examination. The fracture often resembled that of a glass tube or, in the case of thicker walled-cells, the plane of fracture occasionally followed the fibril slope on one side of the cell and gave an irregular saw-toothed edge on the other. Ordinarily the fracture line avoided bordered pits but sometimes passed around the border. Infrequently the wall was torn at a pit, revealing an annular disc of outer layer which was shown from dissection and from birefringent properties

to have concentric fibrillar structure. In some springwood tracheids where fibrillar striations were apparent the lines were seen to fade out over the pit chamber, suggesting an especially closely knit structure of the central layer.

Summerwood fibers of steep fibrillar orientation typically had transverse fracture (pl. 3, figs. 1 and 3). The fracture within the central layer often had a "pipe-organ" pattern, i.e., fibrils or blocks of fibrils projected at uneven distances indicating both concentric and radial cleavage. In some steep-fibrilled specimens of relatively low strength (5-D-3 and 5-D-4) transverse cell fracture commonly sloped across the wall conforming to the slip lines seen in compression failure. Summerwood fibers of high fibrillar angle were commonly fractured along the fibril spiral with secondary planes at irregular angles (pl. 4, fig. 5), but some stronger specimens in this group (pl. 3, fig. 4), as well as those of medium fibrillar angle, exhibited various combinations of spiral and transverse fracture. In this medium fibrillar angle range there was some evidence that the stronger specimens exhibit transverse and "pipe-organ" fiber fracture (pl. 4, fig. 4).

In those cases mentioned in the previous section where summerwood fibers were not broken in the tension fracture of the wood but were slipped apart longitudinally, the plane of fracture was located between the outer and central layers rather than at the middle lamella. Figure 1 of pl. 4 shows some of these apparently unbroken fiber ends from which the outer layer has been slipped. A remnant of outer layer can be seen on the second fiber from the right. Figures 2 and 3 of pl. 4 show a complementary condition where the outer layers which have been pulled off are clinging to whole fiber ends. Figure 3 identifies the outer layer by its weak birefringence.

Lateral separation of fibers at the interface between outer and central layer is demonstrated similarly in pl. 3, figs. 1, 2, and 3.

Compression test fiber fracture.—Compression failure in springwood tracheids appeared as transverse undulating wrinkles in the double walls of adjacent cells without separa-

tion of the cells except at the region of gross fracture. With favorable position of the tracheids in the mount, slip lines were visible at the wrinkles. Some slip lines appeared in summerwood fibers in areas away from the gross fracture with no apparent distortion of the cell wall. At the region of gross fracture the fibers were usually bent in a reverse curve yielding to the diagonal shear plane in the wood, and they were separated at their radial sides. Often these bands appeared to be accentuations of natural bends in the wall at ray crossings (pl. 5, fig. 4) but this was not general. Slip lines were concentrated at the bends.

There appears to be little doubt but that slip lines are actually planes of shear in the central wall. Frequently an offset in the entire wall was seen to be associated with a slip line (pl. 5, fig. 4, upper right, and pl. 6, figs. 1 and 3, lower center). Sometimes bulges on the inner side of a wall were subtended by a pair of slip lines (pl. 5, figs. 1 and 2, upper right). Slip lines were less numerous and less prominent in the fractures of fibers of high fibrillar angle (pl. 6, figs. 5 and 6, pl. 7, fig. 4) where most of the displacement appeared to occur along fibrillar angle planes.

The angle of slip lines with reference to fiber axis had been given in the literature as about 70 degrees. This was observed in the present study to be a good figure for summerwood of "normal" wood, but aside from considerable variations in a single fiber there appeared to be variations in average angle between specimens. Table VII gives some examples of average slip line angles based on small samples.

TABLE VII

AVERAGE ANGLE (AND RANGE) OF SLIP LINES REFERRED TO THE LONGITUDINAL AXIS OF THE CELLS FOR COMPRESSION TESTS IN GREEN CONDITION (DEGREES)

	Low fibrillar angle		High fibrillar angle	
	4-C-1	2-D-2	9-A-4	7-B-4
Summerwood	(70) 72 (76)	(69) 72 (76)	(52) 58 (61)	(66) 68 (72)
Springwood	(52) 57 (62)	(48) 58 (63)	(40) 48 (60)	(41) 49 (59)

As in tension fracture, separation of the cells generally takes place at the interface between outer and central layer, with the middle lamella, primary walls and outer layers clinging to one of two separating cells. Plate 5, figs. 1 and 2, and pl. 6, figs. 1, 2 and 3 show remnants of outer layers that have been detached from adjacent cells. Plate 5, figs. 3 and 4, and pl. 6, fig. 4 show clearly the cleavage between central and outer layer. Because even the brief macerating treatment used here has caused some cell separation at the middle lamella it cannot be definitely stated that there is no mechanical cleavage at this plane. However, the evidence of mechanical cleavage between the layers of the secondary wall was so extensive as to give the impression that this point is normally the center of mechanical weakness between fibers.

In fibers of high fibrillar angle lateral fracture was sometimes not between the outer and central layer but within the central layer (pl. 7, figs. 1, 2 and 3). The central layer seems to be torn along fibrillar angle planes and in planes corresponding to slip lines.

A structural character not previously emphasized in descriptions of "compression wood" but found quite constant in specimens of high fibrillar angle is the thickness of the outer layer of the secondary wall. This outer layer was found to be relatively thick in summerwood fibers for these typically weak specimens. In fibers of medium and low fibrillar angle it varied considerably, and there was some evidence to indicate that thicker outer layers are associated with wood of low strength in its fibrillar angle class.

Figure 1 of pl. 8 shows a macerated fiber from dry tension specimen 1-C-3, a weak specimen of medium fibrillar angle. The outer layer can be plainly identified and appears in best focus on the upper wall at lower right. Figure 2 is the same view under polarized light, with the fiber at the position of maximum brightness. Here the outer layer is not visible since its fibrillar structure at the cell edges is parallel with the light axis. The reduction in apparent diameter of the fiber is partially accounted for by the thickness of the outer layer. The

magnification of the polarized-light pictures was reduced about 10 per cent by insertion of the analyzer. Figs. 3 and 4 are comparable views of a fiber from dry tension specimen 8-A-1, which has about the same average fibrillar angle as 1-C-3 but is much stronger. The two fibers have about the same total diameters in ordinary light but difference in outer layer thickness is shown by the difference in diameters under polarized light.

Specimen 1-C-3 is typical "compression wood" material, and the checks in the central layer which are visible may account for its strength deficiency as compared with specimen 8-A-1 in which checks were not found. Angle of fibrillar orientation, thickness of outer layer, and occurrence of fibrillar checks evidently vary independently.

With the interface between outer and central layer being definitely involved in separation of cells it might be questioned whether the fibrillar slope of the outer layer is important to strength. Very few fibers were found whose fibrillar orientation was not nearly transverse, and these were not confined to specimens of high or low strength.

The occurrence of slip lines appears to be an important influence upon tension strength. They were detected only in specimens which were weak for their fibrillar angles. Figures 5 and 6 of pl. 8 show a fiber from dry tension specimen 5-D-4 of low fibrillar angle and relatively low strength and stiffness in which typical compression slip lines can be faintly seen in the lower wall. End fracture of many fibers in this specimen conformed to these planes.

V. Discussion

The types of variations that may influence the axial strength properties of wood substance (strength of wood with density eliminated) may be enumerated as follows:

A. Architectural
   1. Growth rate
   2. Proportion of summerwood and springwood based on specific gravity

3. Tissue variation
4. Cell morphology

B. Constitutional
1. Cell-wall structure
2. Structure of the central layer
3. Distribution of constituents of the wood substance
4. Chemistry of constituents

This study has been concerned mainly with methods of fracture of a wood of simple anatomy with the aim of identifying the more important of the above variations. As a starting point the characteristics of "compression wood" have afforded clues for the solution of the problem, though no assumption has been made as to the relative importance of such characteristics or as to the interdependence of their variability.

Growth rate has long been associated with weakness in wood, and it still may be a good criterion for absolute strength. However, there is little indication that growth rate in itself has much influence upon the strength of wood substance. Figures 4 to 9 show that in both tension and compression many fast-grown specimens are strong for their density, and "abnormal" material is not excluded from narrower rings. Further, growth rate does not appear in this study to be associated with variations in the strength aside from those dependent upon the character of the cell wall (fibrillar angle).

Percentage of summerwood is an artificial criterion of absolute strength but has not been used in this study. It is recognized that the proportion of summerwood to springwood on the basis of solid volume may be important since it would reflect the relationship between average cell diameter and average cell-wall thickness in the two types of tissue.

In the wood under consideration histological variations appear to be minimized since one tissue preponderates. The variation in area of wood rays and resin ducts has been found by Berkley ('34) to be slight with reference to total sectional area and slight in average percentage between his strongest and weakest compression specimens "per unit weight." It

does not seem that the amount of ray tissue and area occupied by resin canals have considerable effect in determining axial strength properties though a variation in the number of rays may be important since they influence the morphology of tracheids.

Variations in the form of tracheids entail chiefly length, sectional shape and indentations caused by adjacent wood rays, and the occurrence of bordered pits. Since generally fiber fracture occurs in both tension and compression on transverse planes it is not thought that tracheid length is very important. It may influence the tensile strength of specimens in which many fibers are pulled apart longitudinally without fracture of the central layer. In these cases longitudinal shear is involved and the average shear area is less for shorter fibers. Berkley's ('34) outlying compression specimens were not significantly different in fiber length.

Variation of sectional shape from rectangular to circular, though it constitutes one difference between "normal" wood and "compression wood," has not been investigated. Mechanically the advantage in this respect for compression strength would seem to be on the side of the more cylindrical fibers of "compression wood."

The curves in tracheid walls at the edges of wood rays have often been seen in this study as points of fracture in both tension and compression though this is more general in tension fracture than in compression. Correlation of tensile strength with number of rays per unit area may be worthy of investigation since this is known to vary considerably within a tree.

Bordered pits have been proposed as sources of weakness in cell walls, but they rather seem to be in themselves sources of strength in tension. The possibility remains that a preponderance of bordered pits causes weakness because of the deviation of the fibrils of the central layer around them.

The detailed work recently published by Dr. I. W. Bailey and his associates on the constitution of the tracheid wall provides a basis for interpretation of mechanics of the failure of wood substance. The true middle lamella is a very thin

layer of isotropic material separating the cells. This binding material has been mentioned as having influence upon strength but it has been shown in this study as less apt to be a plane of weakness than structural planes within the wall itself. Actually under axial loads separation of cells is usually only incidental to yield within the cell wall. Under compression loads cells separate only when the walls have already failed in diagonal shear. In longitudinal tension, separation appears to be caused by lateral tension between cells resulting from lateral compression within a cell or group of cells, a component of the longitudinal tension force. Evidence of this is seen in the manner of fracture of sheets of double outer layers that obviously have been pulled laterally from between cells (pl. 3, fig. 3). In those cases where the central layer is not fractured in axial tension (pl. 4, fig. 1), failure occurs from longitudinal shear between outer and central layer. The lateral fracture within the central layer (pl. 7, figs. 1, 2 and 3) is interesting in view of findings of Bailey and Kerr ('37), that the two layers of the secondary wall in "Rotholz" tracheids are separated by "an isotropic layer of non-cellulosic composition." It would appear that the isotropic material is stronger in tension than is the cellulose structure perpendicular to its orientation plane.

The primary wall has not been identified with mechanical failure, and it is probable that it is so closely associated with the amorphous material of the middle lamella that it does not act independently.

Wide variation in the thickness of the outer layer of the secondary wall in summerwood leads to the conclusion that this may be an important measurable criterion for axial strength. The fibrils here approach transverse orientation and are at least an advantage in resistance to longitudinal or local shear stresses. Further, the peripheral position of the layer causes slight deviations in thickness to be reflected in disproportionate changes in sectional area of the cell wall. As an example, measurements from pl. 8, figs. 1 to 4 may be given. When diametrical measurements are made on the photographs (considering the difference in magnification between ordinary

and polarized light) and the circular areas of the layers computed, it is seen that the outer layer has 52 per cent of the total wall area in the fiber of 1-C-3 and only 26 per cent in the fiber of 8-A-1. The thicknesses of the outer layer indicated by this method of observation are 4.2 μ and 2.4 μ respectively. Because the sections of the fibers are not circular as has been assumed in this example and because of the possibility of optical error, this technique is not recommended for measuring the variable. However, justification for work on an accurate method of measurement in connection with strength studies is indicated.

That the characteristics of the central layer of the secondary wall are the most important criterion of axial mechanical properties of wood substance is suggested by the fact that variations in stiffness dependent upon fibrillar angle are greater than the remaining variations (figs. 10 to 15). This evidence is not seen in the consideration of ultimate strength, and it might be assumed that different factors affect stiffness and strength. It is more probable that the greater variation in ultimate strength is caused by uneven distribution of stresses and consequent local failure precipitating the failure of the specimen. Thus modulus of elasticity is probably the best measure of average mechanical resistance.

There appears to be some connection between the relationships of stiffness with fibrillar angle and what we now know of the structure of the cell wall and its method of fracture. Resistance in tension is about twice that in compression in fibers of steep angle. In this type of fiber, tension fracture has been shown to result from longitudinal strain on the elongated cellulose framework; the system is broken. Compression fracture in these fibers is a result of diagonal shear strain (along slip lines) across the concentric density laminae of the cellulose system. Actual rupture is not usually visible, and it is probable that there is involved only distortion, perhaps bending of fibrils similar to that in gross fracture.

Stiffness in tension is shown to be only slightly higher than that in compression in fibers of high fibrillar angle. Here both

tension and compression fracture are seen to result from shear strain between the fibrils or along the radio-helical discontinuities in the cellulose framework shown by Bailey and Kerr ('37) to occur in "compression wood." This is undoubtedly because the fibrillar angle approaches the theoretical 45° angle of shear which tends to operate under simple loading. An additional reason applicable to the compression mechanism is the radial density pattern in the central layer, providing resistance to shear across the wall.

Further evidence that the mechanism of resistance for compression is different from that of tension is seen by an examination of the effect of drying. Stiffness in tension is increased about the same amount throughout the range of fibrillar angle, which is only slightly less than the increase for compression stiffness at high fibrillar angles. At low angles for compression stiffness the increase is approximately doubled. It seems a logical conclusion that shear across fibrils (slip lines) is more concerned with secondary valences than is inter-fibrillar shear.

Since the transition from normal to "compression wood" is a gradual one, changes in fibrillar angle are perhaps more or less accompanied by changes in other characters, and it may not be stated positively that the dependence shown in these charts is attributable solely to the measured variable. However, this study indicates that some of the structural features of "compression wood" do not vary concurrently. Proportion of outer layer in the secondary wall and pattern of density variation in the central layer are two characters which are worthy of further investigation in a search for causes of variation from the relationships of axial strength to fibrillar angle. Quantitative criteria for the latter feature might be found in the angle of slip lines and the frequency of central wall checks. It may be discovered that the change from concentric to radial density pattern is a positive influence on compression strength since it tends to inhibit the formation of slip lines.

Koehler ('33) has stated that compression damage, sustained in the tree and indicated by slip lines, is a cause of brashness in tension. This seems to be confirmed in this study

where slip lines are associated with relatively low tension strength (pl. 8, figs. 5 and 6). There is a possibility that tension strength is affected by this factor without detection, i.e., the damage may be so slight that slip lines are invisible with technique now available.

Summary

The factors necessary of consideration in a complete study of the strength properties of coniferous wood are reviewed with stress upon the structure of the tracheid wall.

Four series of engineering strength tests are reported for carefully chosen specimens representing nine logs of commercial shortleaf pine wood; (1) axial tensile strength, green wood, (2) axial tensile strength, air-dry wood, (3) axial compression strength, green wood, (4) axial compression strength, air-dry wood. Ultimate strength and modulus of elasticity are given for each test. The factor, specific gravity, is eliminated from the comparisons of specimens by expressing mechanical properties as "strength-density index" (ultimate strength ÷ specific gravity), and "stiffness-density index" (modulus of elasticity ÷ specific gravity).

These indexes are plotted over growth rate, showing that this is not a universal criterion of mechanical properties of wood substance, though it controls the frequency of occurrence of weak specimens.

The indexes are correlated with the sine of the average angle of fibrillar orientation in summerwood, resulting in significant product-moment correlation coefficients in all cases except one in which the distribution of the data is obviously inadequate. Variations from the regression lines are not connected with growth rate.

Examination of tension fractures under low-power binocular microscope revealed the following:

(1) The typical brash gross failure observed for strong dry wood is not of the same cellular detail as that exhibited by weak specimens.

(2) Fracture of springwood cells is determined generally by the plane of shear stress for the wood.

(3) At longitudinal cleavage planes in summerwood, fragments of outer layer are seen clinging to apparently whole cells, indicating that cell separation may occur between outer and central layers of the secondary wall rather than at the middle lamella. Longitudinal cleavage in springwood is fracture through the cells.

(4) End fracture of radial rows of tracheids often occurs at the intersection of these cells with one edge of a wood ray.

(5) Some fibers, unfractured in tension, are seen in strong dry specimens and more widely distributed in the green series.

(6) There is some evidence that brash failure is associated with relatively low strength among specimens of steep fibrillar angle and that splintering occurs with relatively high strength at high fibrillar angles.

The principal observations in microscopic examination of isolated fibers of tension specimens are as follows:

(1) Bordered pits are not sources of weakness.

(2) Concentric arrangement of fibrils in the outer layer of the secondary wall at bordered pits is confirmed.

(3) Springwood cells generally fracture in no definable pattern.

(4) Fibers of steep fibrillar orientation have transverse fracture with some independent fracture of groups of fibrils; some of the weaker specimens have fiber fracture conforming to typical compression slip lines.

(5) Summerwood fibers of high fibrillar angle fail mostly along fibrillar planes with some secondary planes of irregular angle.

(6) Medium fibrillar angles are associated with various combinations of transverse and spiral fracture, with stronger fibers favoring the transverse type.

(7) Lateral separation of fibers is seen to occur mostly, if not always, at the interface between outer and central layers of the secondary wall.

(8) Where fibers are not fractured in tension, failure is indicated as longitudinal shear between outer and central layer.

The following observations concern fibers in compression specimens:

(1) Slip lines are confirmed as planes of shear on the cell wall.

(2) Fracture of fibers of steep fibril angle is seen as bending in the cell wall where slip lines are concentrated.

(3) Fiber fracture at high fibrillar angles follows fibrillar planes.

(4) Cell separation is normally between outer and central layers of the secondary wall.

(5) Cell separation in summerwood fibers of high fibrillar angle may occur within the central layer.

(6) There is some evidence that slip line angles are greater in material of low fibrillar angle.

Wide variation is shown to occur in thickness of outer layer, with greater thickness mostly associated with greater fibrillar angle.

The relative importance of the factors that may affect the axial strength properties of wood is discussed, and it is concluded that the factors most likely connected with variations remaining after control of specific gravity, moisture, and fibrillar angle are:

(1) Proportion of springwood and summerwood by weight.

(2) Proportion of outer layer to central layer of the secondary wall by sectional area.

(3) For compression strength—variation of angle of slip lines and frequency of fibrillar checks.

(4) For tension strength—number of wood rays per unit of tangential area.

(5) For tension strength—the degree of compression damage previously sustained as seen by the occurrence of slip lines.

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Explanation of Plate

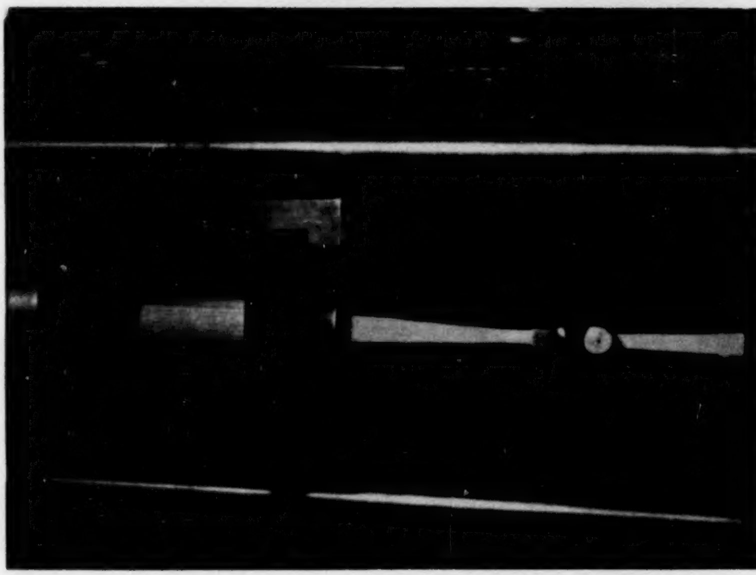
PLATE 1

Fig. 1. Drill press with shaper arranged for finishing test sections of tension specimens.

Fig. 2. Tension specimen in Amsler hydraulic testing machine with extensometer in place.

[*Note.* An error has been made in labeling all of the accompanying plates Volume 27 instead of Volume 26.]

1



2

GARLAND—WOOD STRENGTH AND MICROSCOPIC STRUCTURE

EXPLANATION OF PLATE

PLATE 2

Cross-section from the middle of the 2½-inch planks used for testing, with positions of specimens indicated.

1 2 3 4 5 6 7 8 9

GARLAND—WOOD STRENGTH AND MICROSCOPIC STRUCTURE

Explanation of Plate

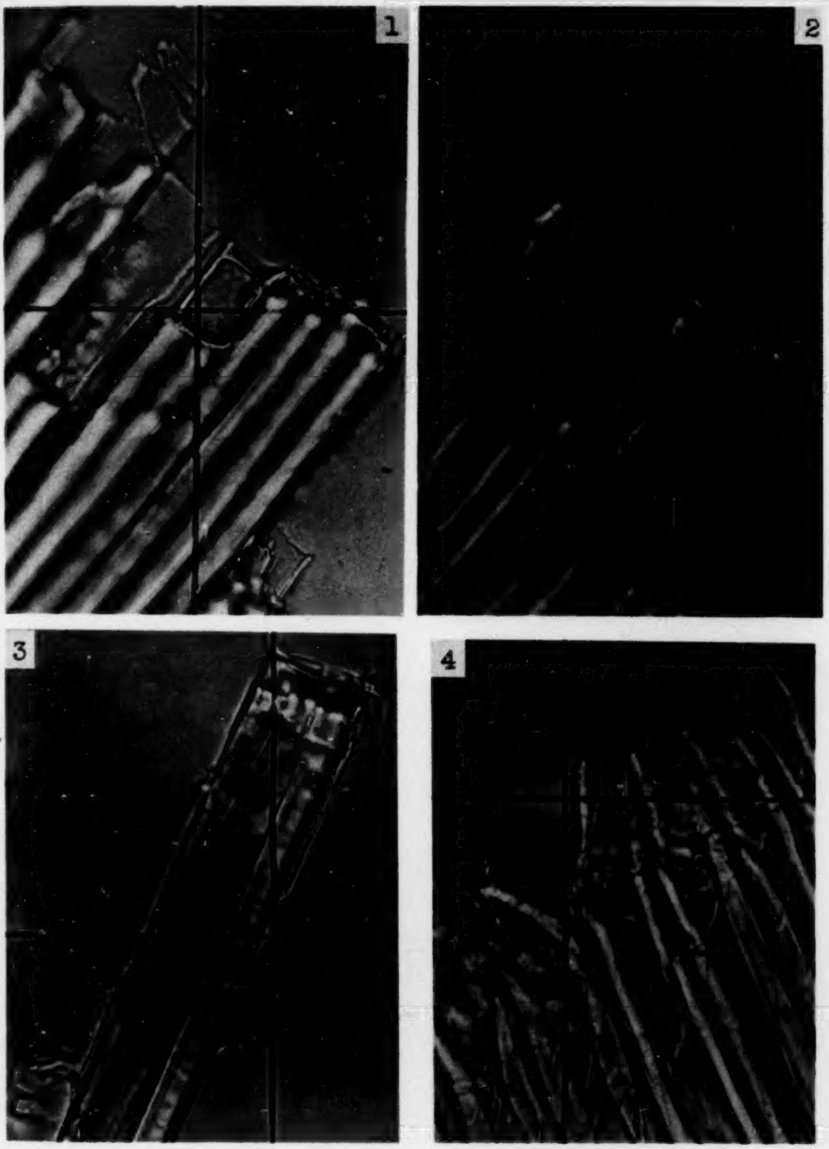
PLATE 3

Fig. 1. Radial group of summerwood tracheids from green tension specimen 8-C-4, showing typical transverse and "pipe-organ" fracture of strong fibers. Note sleeves of outer layer projecting. × 440.

Fig. 2. Same as fig. 1 with analyzer inserted. × 396.

Fig. 3. Summerwood tracheid from green tension specimen 2-C-2, showing typical end fracture of strong fibers and fracture of outer layer due to lateral separation. × 440.

Fig. 4. Radial group of summerwood tracheids from dry tension specimen 2-A-6, showing combination of spiral cleavage and transverse fracture. This specimen is relatively strong for its high fibrillar angle (sine, .550). × 440.



GARLAND—WOOD STRENGTH AND MICROSCOPIC STRUCTURE

Explanation of Plate

PLATE 4

Fig. 1. Radial group of summerwood tracheids from green tension specimen 9-C-1 at fracture, showing fiber ends whole, common in strong specimens. It is evident that these tips consist of a central layer from which the outer layer has been pulled. × 440.

Fig. 2. Radial group of summerwood tracheids from green tension specimen 6-B-2, showing method of fracture common for strong fibers. The central layers of the secondary wall are unbroken and separation has occurred between the central and outer layers. Note sleeves and sheets of outer layer projecting. × 100.

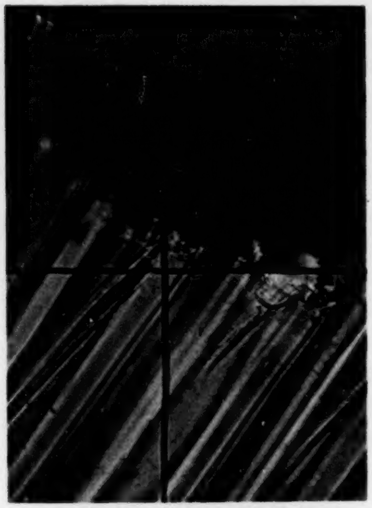
Fig. 3. Same as fig. 2 with analyzer inserted. × 90.

Fig. 4. Radial group of summerwood tracheids from dry tension specimen 3-D-5, showing fracture of the "pipe-organ" type and separation along the fibrils. This specimen is of medium fibrillar angle (sine, .310) and is relatively strong. × 440.

Fig. 5. Radial group of summerwood tracheids from green tension specimen 9-A-4, showing typical spiral fracture of fibers of high fibrillar angle (sine, .510). × 100.

Fig. 6. Radial group of springwood tracheids from dry tension specimen 3-D-5, showing typical irregular fracture. × 100.

1



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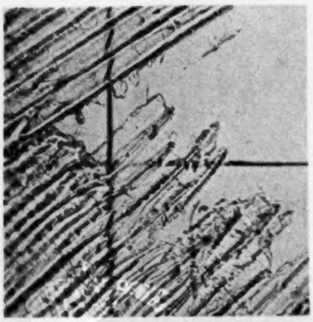

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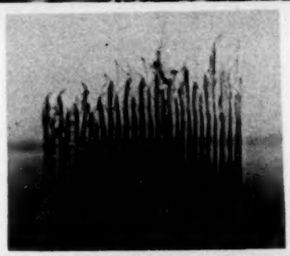


3

6

GARLAND—WOOD STRENGTH AND MICROSCOPIC STRUCTURE

Explanation of Plate

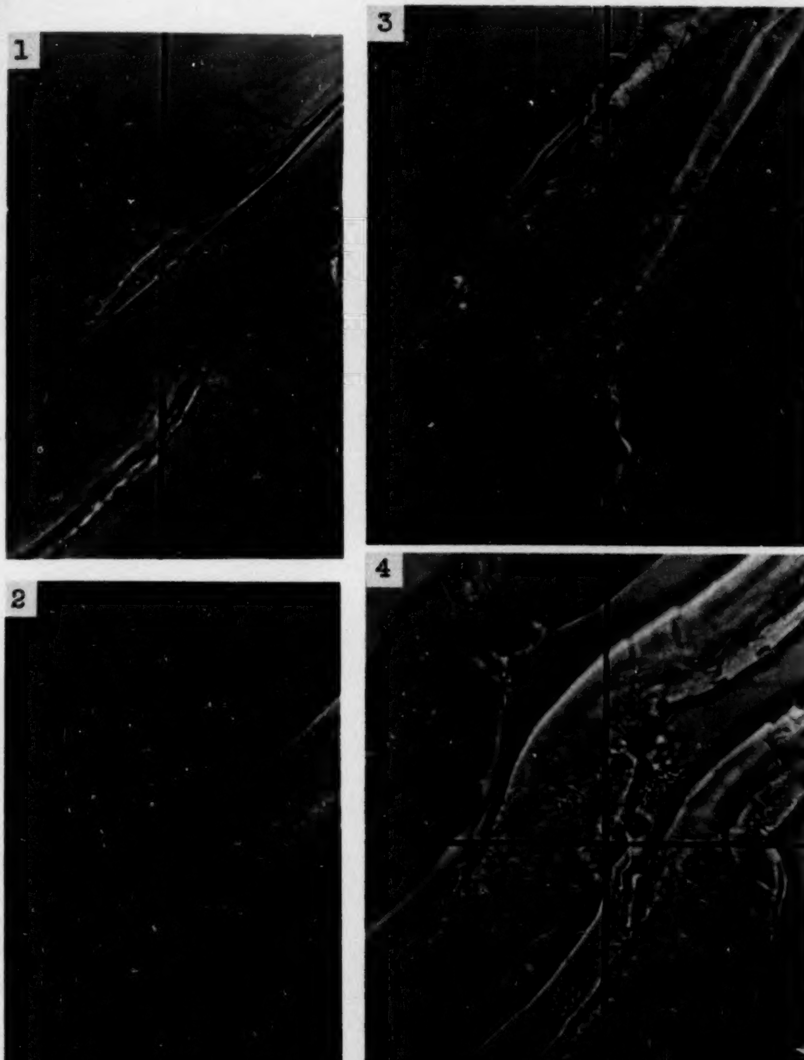
PLATE 5

Fig. 1. Summerwood tracheid from dry compression specimen 4-A-1 at fracture, showing prominent slip lines and rupture of the outer layer. The fragment of outer layer above belongs to an adjacent cell and has been partially separated at the middle lamella by maceration. × 440.

Fig. 2. Same as fig. 1 with analyzer inserted. × 396.

Fig. 3. Summerwood tracheid from green compression specimen 2-D-2 at fracture, showing slip line concentration typical of strong fibers and rupture between central and outer layers. × 440.

Fig. 4. Tangential view of a radial group of summerwood tracheids from dry compression specimen 2-B-2, showing prominent slip lines associated with displacements of wall material. The bend above is coincident with a ray crossing and the creases occur at the pits. × 440.



GARLAND—WOOD STRENGTH AND MICROSCOPIC STRUCTURE

EXPLANATION OF PLATE

PLATE 6

Fig. 1. Summerwood tracheid from dry compression specimen 4-A-1 at fracture, showing prominent slip lines associated with displacements (diagonal shear) in the walls and with movement of the wall material into the lumen. × 440.

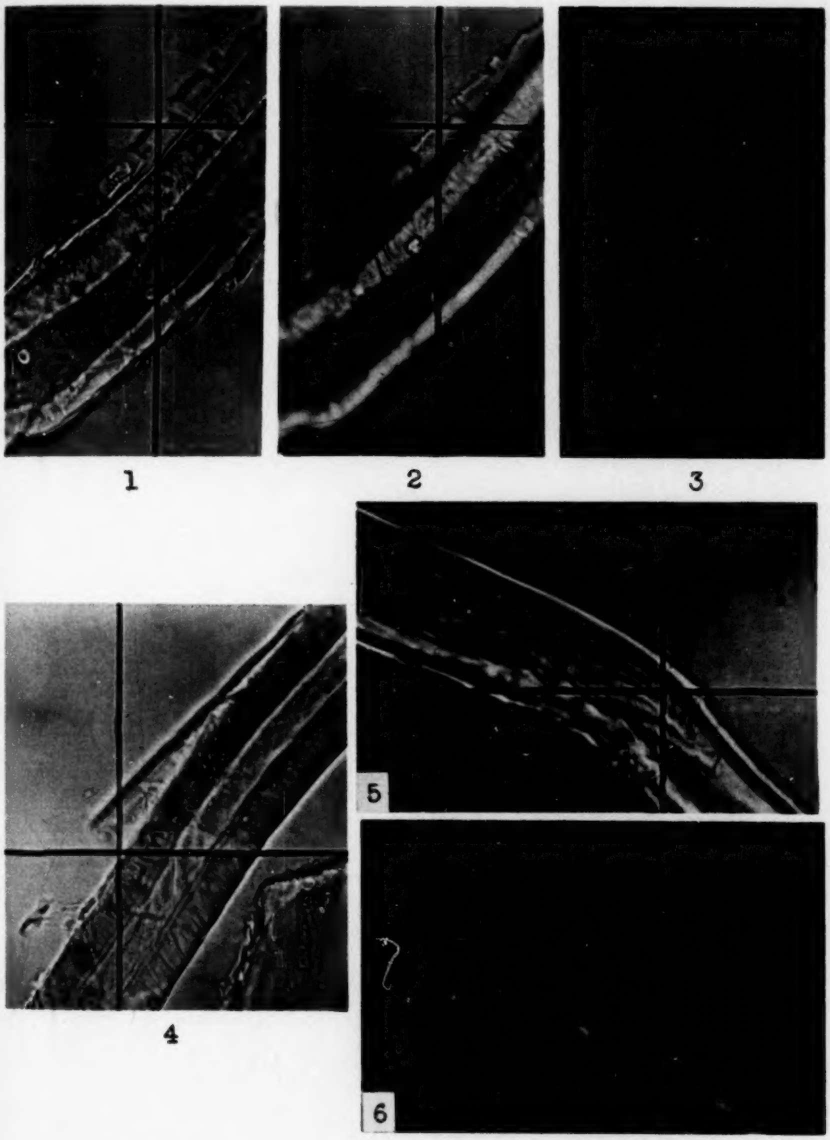
Fig. 2. Same as fig. 1 with focus on a sheet of outer layer at upper right showing it to be a remnant of an adjacent cell. × 440.

Fig. 3. Same as fig. 1 with analyzer inserted. × 396.

Fig. 4. Summerwood tracheid from dry compression specimen 7-B-4 at fracture, showing slip lines and separation of outer layer from central layer. × 440.

Fig. 5. Summerwood tracheid from green compression specimen 9-A-4 at fracture, showing few slip lines and thick outer layer which is apparently not closely associated with the central layer. This is a typical "compression wood" fiber with high fibrillar angle (sine, .490) and prominent checks in the central layer. × 440.

Fig. 6. Same as fig. 5 with analyzer inserted. × 396.



GARLAND—WOOD STRENGTH AND MICROSCOPIC STRUCTURE

EXPLANATION OF PLATE

PLATE 7

Fig. 1. Radial group of summerwood tracheids from green compression specimen 7-A-4 at fracture, showing method of separation that may occur between fibers of high fibril angle (sine, .450). Lateral rupture has occurred mostly within the central layer and has followed planes of slip lines and of fibril orientation. Focus on radial view at left. × 440.

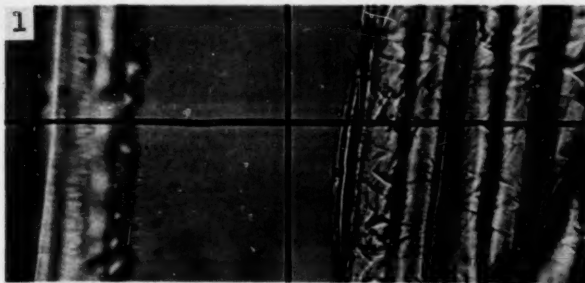
Fig. 2. Same as fig. 1 with focus on a single fiber that has become detached from the group and turned to present a tangential view. × 440.

Fig. 3. Summerwood tracheid from green compression specimen 7-A-4 at fracture, showing rupture of the central layer of the secondary wall due to lateral separation. × 440.

Fig. 4. Radial group of summerwood tracheids from dry compression specimen 9-D-4 at fracture, showing thick outer layer and scarcity of slip lines typical of fibers with high fibrillar angle (sine, .410). The fiber at the right has fractured along planes of the fibrillar checks. × 440.

Fig. 5. Group of summerwood tracheids from green tension specimen 7-A-4 of rather high fibrillar angle (sine, .390), showing thick outer layer and absence of checks. This specimen is relatively low in strength. × 440.

Fig. 6. Same as fig. 5 with analyzer inserted. × 396.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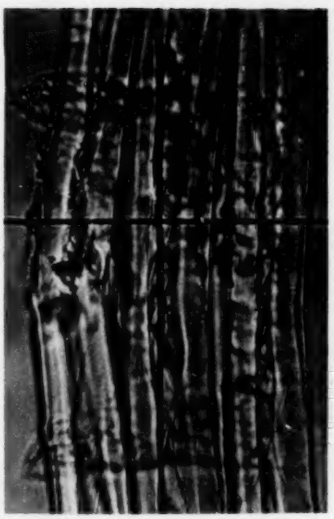
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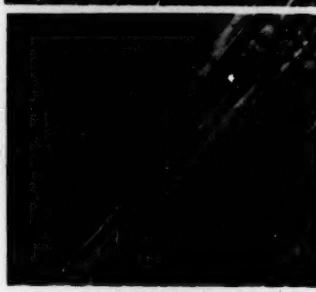
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GARLAND—WOOD STRENGTH AND MICROSCOPIC STRUCTURE

EXPLANATION OF PLATE

PLATE 8

Fig. 1. Summerwood tracheid from dry tension specimen 1-C-3 of medium fibrillar angle (sine, .330), showing relatively thick outer layer and prominent checks in the central layer. This specimen is weak in comparison with specimen 8-A-1 (figs. 3 and 4). × 440.

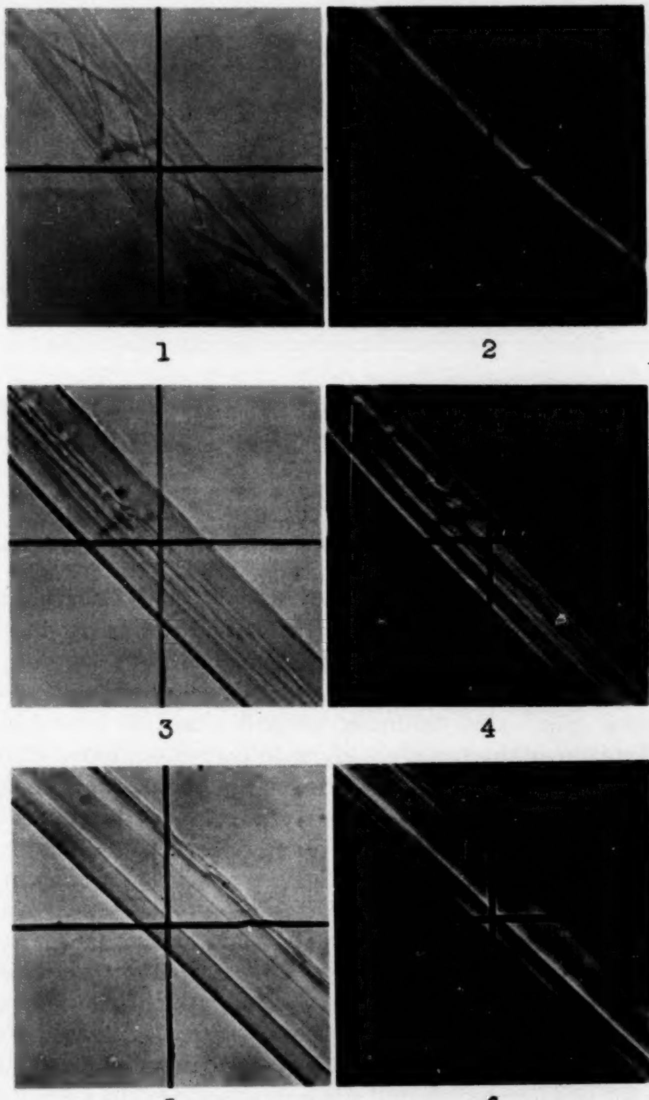
Fig. 2. Same as fig. 1 with analyzer inserted. × 396.

Fig. 3. Summerwood tracheid from dry tension specimen 8-A-1 of medium fibrillar angle (sine, .350) showing outer layer relatively thin and absence of checks. This specimen is strong in comparison with specimen 1-C-3. × 440.

Fig. 4. Same as fig. 3 with analyzer inserted. × 396.

Fig. 5. Summerwood tracheid from dry tension specimen 5-D-4 of low fibrillar angle (sine, .110) and relatively low strength showing slip lines which may have been present before the test. × 440.

Fig. 6. Same as fig. 5 with analyzer inserted. × 396.



GARLAND—WOOD STRENGTH AND MICROSCOPIC STRUCTURE